

ANÁLISIS DEL CONTROL PREDICTIVO DE
CORRIENTE APLICADO AL FILTRO ACTIVO
DE POTENCIA BASADO EN CONVERTIDORES
EN CONFIGURACIÓN PUENTE-H DE DOS
NIVELES



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EN CONFIGURACIÓN PUENTE-H DE DOS NIVELES**

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RESUMEN

En los últimos años debido al aumento de las cargas no lineales en la red de distribución eléctrica, tales como los dispositivos electrónicos, transformadores y de tracción, se ha producido un aumento de los armónicos y el consumo de la potencia reactiva en la red de distribución eléctrica y en consecuencia el deterioro de la calidad de energía en la red de distribución. Algunos efectos principales de la mala calidad de energía son; distorsión armónica, cortes en el suministro, oscilaciones de tensión, fenómenos transitorios, caídas y picos de tensión. La necesidad de dar respuesta a esta problemática de manera a cumplir con las normativas vigentes, ha motivado el diseño de topologías más eficientes de filtros activos de potencia (APFs) capaces de compensar independiente o simultáneamente los problemas asociados a la calidad de energía en la red de distribución eléctrica. Existen varios tipos de APFs como el APF de derivación (SPAF), compensador estático síncrono (STATCOM), APF serie y el APF híbrido, en donde el STATCOM es utilizado principalmente para compensar la potencia reactiva, armónicos y la circulación de la corriente por el punto neutro en sistemas trifásicos de cuatro hilos con carga desbalanceada. Una de las topologías más abordadas recientemente es el STATCOM paralelo de dos niveles, basado en una conexión de convertidores Puente-H, lo cual tiene ventajas como su característica modular, escalabilidad y bajo costo computacional.

Por otra parte, el desarrollo y evolución de los convertidores de potencia han aumentado en los últimos años debido a la gran cantidad de aplicaciones que incluyen estos dispositivos, entre ellas se cuenta la conversión de la energía, tracción eléctrica, máquinas y generación distribuida. El control de estos dispositivos como los controles lineales, por histéresis, lógica difusa, modo deslizante, el control predictivo y otros, han sido un tema muy estudiado, ya que se requiere convertir la energía eficientemente para aprovechar al máximo la generación de esta. El control predictivo basado en modelos (MPC) es una estrategia prometedora para el control de convertidores, la cual tiene como característica el uso de modelos matemáticos del sistema para predecir comportamientos futuros y seleccionar acciones de control apropiadas. Dentro de las ventajas del MPC esta la posibilidad de controlar varias variables con una sola ley de control, esto puede lograrse mediante la introducción de los objetivos de control en la función de costo, en donde cada término adicional en la función tiene un factor de ponderación específico. Estos parámetros tienen que ser diseñados correctamente con el objetivo de lograr el rendimiento deseado, ya que la mala elección de éstos puede provocar la inestabilidad del sistema.

Sin embargo, algunas cuestiones que constituyen una desventaja para el método de control MPC, es que opera a una frecuencia de conmutación variable y solo puede seleccionar un número limitado de estados de conmutación válidos, debido a la ausencia de un modulador. Esto genera armónicos, así como grandes rizados en la tensión y corriente, con una propagación del espectro, disminuyendo el rendimiento del sistema en términos de la calidad de potencia.

Esta Tesis de Maestría, analiza y aplica la estrategia de control MPC al APF trifásico de cuatro hilos en configuración Puente-H de dos niveles con el objetivo de compensar la potencia reactiva y eliminar la corriente del neutro para carga desbalanceada, para luego pasar al objetivo de analizar y diseñar una estrategia de modulación con control predictivo a través de un patrón de conmutación, para el convertidor Puente-H de dos niveles, con el fin de disminuir el rizado de corriente del convertidor, y consecuentemente disminuir la distorsión armónica total (THD).

Esto se realizó primeramente para el APF monofásico de dos niveles en configuración Puente-H y luego en el trifásico. El método de control predictivo MPC con modulación por patrón de conmutaciones, evalúa todos los estados de conmutación factibles, aprovechando la naturaleza discreta del convertidor, luego la acción de control se escoge mediante el algoritmo, seleccionando dos funciones de costo mediante los dos vectores activos para finalmente aplicar un patrón de conmutación que se puede escoger flexiblemente y a criterio del diseñador, el cual tiene relación directa con la modulación.

Para validar las propuestas de esta Tesis se utilizó un entorno MatLab/Simulink el cual se simuló el método de modulación propuesto. Se observó que este sistema es capaz de

compensar la potencia reactiva y disminuir el rizado del convertidor, el cual se compara las mediciones de THD de la corriente inyectada por el APF con el método de control clásico para validar la propuesta de modulación. Como resultado de esta investigación, se han presentado en congresos internacionales los siguientes artículos:

Artículo 1: A. Renault, M. Rivera, J. Rodas, L. Comparatore, J. Pacher and R. Gregor, "Model Predictive Current Control with Neutral Current Elimination for H-Bridge Two-Level Active Power Filters," *IEEE Ecuador Technical Chapters Meeting: ETCM*, Guayaquil, Ecuador, DOI: 10.1109/ETCM.2016.7857653, Oct. 12-14, 2016.

Artículo 2: A. Renault, M. Rivera, J. Rodas, L. Comparatore, J. Pacher and R. Gregor, "Modulated Model Predictive Current Control for H-Bridge Two-Level Single Phase Active Power Filters STATCOM," *IEEE Conference on Industrial Electronics and Applications: ICIEA*, Siem Reap, Camboya, jun. 18-20, 2017.

Artículo 3: A. Renault, J. Rodas, R. Gregor and M. Rivera, "Modulated Model Predictive Current Control for H-Bridge Two-Level Three Phase Active Power Filters STATCOM," en redacción.

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SUMMARY

In recent years, due to the increase in non-linear loads in the electrical distribution network, such as electronic devices, transformers and traction, there has been an increase in harmonics and the consumption of reactive power in the distribution grid and consequently the deterioration of the quality of energy in the distribution grid. Some main effects of poor power quality are; harmonic distortion, power outages, voltage fluctuations, transient phenomena, falls and voltage peaks. The need to respond this problem in order to comply with current regulations has motivated the design of more efficient topologies of active power filters (APFs) capable of independently or simultaneously compensating the problems quality on power grid distribution. There are several types of APFs such as APF shunt (SPAF), synchronous static compensator (STATCOM), APF series and APF hybrid, where STATCOM is mainly used to compensate for reactive power, harmonics and current flow through the neutral point in three-phase four-wire systems with unbalanced load. One of the most recently addressed topologies is the parallel two-level STATCOM, based on a connection of H-bridge converters, which has advantages such as modular feature, scalability and low computational cost.

On the other hand, the development and evolution of power converters have increased in recent years due to large number of applications that include these devices, including

energy conversion, electric traction, machines and distributed generation. The control of these devices such as linear controls, hysteresis, fuzzy logic, sliding mode, predictive control and others, have been a well studied topic, since it's necessary to convert energy efficiently to maximize the generation of this. Model-based predictive control (MPC) is a promising strategy for converter control, which features the use of mathematical models of the system to predict future behaviors and select appropriate control actions. Within the advantages of the MPC is the possibility of controlling several variables with a single control law, this can be achieved by introducing the control objectives in the cost function, where each additional term in the function has a weighting factor specific. These parameters have to be designed correctly in order to achieve the desired performance, since poor choice of these can cause system instability.

However, some issues constituting a disadvantage for the MPC control method is that it operates at a variable switching frequency and can only select a limited number of valid switching states due to absence of a modulator. This generates harmonics as well as large ripples in the voltage and current, with a spread of the spectrum, decreasing the performance of the system in terms of power quality.

This Master's thesis analyzes and applies the MPC control strategy to APF three-phase four-wire two-level H-Bridge configuration in order to compensate the reactive power and eliminate the neutral current for unbalanced load, and then the objective of analyzing and designing a modulation strategy with predictive control through a switching pattern for two-level H-Bridge converter, in order to reduce the converter current ripple, and consequently decrease the total harmonic distortion (THD).

This was done first for the two-phase single-phase APF in H-Bridge configuration and then in three-phase. The MPC predictive control method with commutation pattern modulation evaluates all feasible switching states, taking advantage of the discrete nature of the converter, then the control action is chosen by the algorithm, selecting two cost functions by means of two active vectors for finally applying a switching pattern that can be chosen flexibly and at the discretion of the designer, which is directly related to modulation.

To validate the proposals of thesis we used a MatLab/Simulink environment which simulated the proposed modulation method. It was observed that this system is able to compensate the reactive power and decrease the ripple of the converter, which compares the THD measurements of the current injected by the APF with the classical control method to validate the proposed modulation. As a result of this research, the following papers have been presented at international congresses:

Paper 1: A. Renault, M. Rivera, J. Rodas, L. Comparatore, J. Pacher and R. Gregor, "Model Predictive Current Control with Neutral Current Elimination for H-Bridge Two-Level Active Power Filters," *IEEE Ecuador Technical Chapters Meeting: ETCM*, Guayaquil, Ecuador, DOI: 10.1109/ETCM.2016.7857653, Oct. 12-14, 2016.

Paper 2: A. Renault, M. Rivera, J. Rodas, L. Comparatore, J. Pacher and R. Gregor, "Modulated Model Predictive Current Control for H-Bridge Two-Level Single Phase Active Power Filters STATCOM," *IEEE Conference on Industrial Electronics and Applications: ICIEA*, Siem Reap, Camboya, jun. 18-20, 2017

Paper 3: A. Renault, J. Rodas, R. Gregor and M. Rivera, "Modulated Model Predictive Current Control for H-Bridge Two-Level Three Phase Active Power Filters STATCOM." in writing.

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*Dedicado a
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ACRÓNIMOS

AC	Corriente alterna.
APF	Filtro activo de potencia.
CC	Corriente continua.
CHB	Convertidor en configuración Puente-H en cascada.
DC-link	Enlace de corriente directa.
DPC	Control de potencia directa.
DVR	Restaurador dinámico de voltaje.
FACTS	Sistema flexible de transmisión de corriente alterna.
FCI	Convertidor de capacitor flotante.
FCS-MPC	Control predictivo de estados finitos.
MC	Convertidores matriciales.
MPC	Control predictivo basado en modelo.
MSE	Error cuadrado medio.

NPC	Punto neutro de fijación.
PCC	Punto de acoplamiento común.
PI	Controlador proporcional e integral.
PF	Factor de potencia.
PfSF	Frecuencia de conmutación fija.
PLL	Bucle cerrado de fase.
PvSF	Frecuencia de conmutación variable.
PWM	Modulación por ancho de pulso.
rms	Valor cuadrático medio.
SAPF	APF de derivación.
STATCOM	Compensador estático síncrono.
SVM	Modulación vectorial espacial.
THD	Distorsión armónica total.
VSC	Convertidor de fuente de tensión.
VSI	Convertidor de fuente de tensión.
UPS	Sistema de alimentación ininterrumpida.
UPQC	Acondicionador de calidad de energía unificada.

SÍMBOLOS

i	Predicción de corriente.
i^*	Referencia de la corriente.
g_i	Función de costo de corriente.
v	Predicción de voltaje.
v^*	Referencia de voltaje.
g_v	Función de costo de voltaje.
P	Predicción de potencia activa.
P^*	Referencia de potencia activa.
Q	Predicción de potencia reactiva.
Q^*	Referencia de potencia reactiva.
g_{PQ}	Función de costo de potencia activa y reactiva.
λ	Factor de ponderación.
ϕ_1	Ángulo de fase de la corriente fundamental de carga.

θ_s	Ángulo de fase de la corriente fundamental de la red.
I_{L1}	Amplitud rms de la corriente fundamental de carga.
I_{Lh}	Amplitud rms de la corriente armónica de carga.
ϕ_h	Ángulo de fase de la armónica corriente de carga.
ϕ_h	Ángulo de fase de la armónica corriente de carga.
$i_L(\theta_s)$	Corriente de carga no lineal.
I_{rms}	Corriente rms total de carga.
S	Potencia aparente.
CF	Factor de cresta.
DF	Factor de distorsión.
T	Matriz de transformación.
a	Fase R de la red eléctrica trifásica.
b	Fase S de la red eléctrica trifásica.
c	Fase T de la red eléctrica trifásica.
n	Neutro de la red eléctrica trifásica de cuatro hilos.
k	Tiempo actual.
Z_L	Carga.
Z_s	Impedancia del sistema eléctrico.
S_a	Señales de activación de los transistores del convertidor.
$\alpha - \beta$	Plano de proyección ortogonal en el marco de referencia estacionario.
i_s^{abcn}	Corriente de la red eléctrica de las fases a , b , c y n .
i_L^{abcn}	Corriente de la carga de las fases a , b , c y n .
i_c^{abcn}	Corriente del filtro de las fases a , b , c y n .
i_c^{abcn*}	Referencia de corriente del filtro de las fases a , b , c y n .
$i_c^{abcn}(k)$	Corriente medida a la salida del APF de las fases a , b , c y n .
$i_c^{abcn}(k+1)$	Corriente predicha en el instante $(k+1)$ del filtro de las fases a , b , c y n .
$ei_c^{abcn}(k+1)$	Error predicho las fases a , b , c y n .
$g(k+1)$	Función de costo predicho
$i_{c\alpha}^*$	Corriente de referencia del APF en el eje α

$i_{c\beta}^*$	Corriente de referencia del APF en el eje β
i_{c0}^*	Corriente de referencia de secuencia cero del APF
i_{L0}^*	Corriente de referencia del APF en el eje β
Q_c	Potencia reactiva instantánea del APF.
Q_c^*	Referencia de la potencia reactiva instantánea del APF.
Q_s	Potencia reactiva instantánea de la red eléctrica.
Q_L	Potencia reactiva instantánea de la carga.
P_c	Potencia activa instantánea del APF.
P_s	Potencia activa instantánea de la red eléctrica.
P_L	Potencia activa instantánea de la carga.
P_{c0}	Potencia instantánea de secuencia cero.
f_c	Frecuencia de la red.
f_m	Frecuencia de conmutación.
$v_s^{abcn}(k)$	Tensión de la red eléctrica medida de las fases a , b , c y n .
$v_c^{abcn}(k)$	Tensión medida a la salida del APF de las fases a , b , c y n .
v_c^a	Tensión del APF de la fase a .
v_{DC}	Tensión del convertidor.
R_f	Resistencia del filtro.
I_f	Inductancia del filtro.
R_L	Resistencia de la carga.
I_L	Inductancia de la carga.
T_s	Tiempo de muestreo.

Parte I

GENERALIDADES

CAPÍTULO 1

INTRODUCCIÓN

1.1. Consideraciones preliminares

El estudio de los convertidores de potencia ha experimentado un constante crecimiento durante la última década, debido a la gran cantidad de aplicaciones que incluyen estos dispositivos, entre ellas se tiene la conversión de la energía, tracción eléctrica, máquinas y generación distribuida [1]. Una de las áreas de mayor estudio se centró en el control de estos convertidores, ya que se requiere convertir la energía eficientemente para aprovechar al máximo la generación de esta, para ello existen diversas estrategias de regulación, los más utilizados son las técnicas convencionales, como el control por histéresis y el controlador PI [2].

Hoy en día, gracias a la evolución y el aumento en la capacidad de microprocesadores y tecnologías de procesamiento de señales, éstos han permitido la implementación de métodos de control modernos diseñados para satisfacer la creciente demanda de los convertidores en la industria [3]. El MPC ha focalizado recientemente el interés de la comunidad científica internacional como una alternativa viable frente a los controladores

convencionales, para el control de convertidores de potencia y los distintos tipos de accionamientos electromecánicos [4]. La principal característica del esquema MPC es la utilización del modelo matemático del proceso a controlar, de manera a realizar las predicciones futuras de las variables de estado [5], [6].

En esta Tesis de Maestría se propone un análisis mediante simulación del control predictivo de corriente aplicado al APF de dos niveles basado en convertidores en configuración Puente-H, en los sistemas monofásico, trifásicos de tres y cuatro hilos, con una propuesta de modulación por patrón de conmutación.

1.2. Objetivos

1.2.1. Objetivos generales

Realizar el estudio teórico mediante simulaciones del control predictivo de corriente aplicado al APF basado en convertidores de dos niveles en configuración Puente-H, enfocados en la mejora de la calidad de la potencia eléctrica.

1.2.2. Objetivos específicos

- Investigar los APFs, sus ventajas, desventajas, aplicaciones y estrategias de control.
- Estudiar y analizar las técnicas de control basadas en la estrategia MPC, para su aplicación en el control de APFs.
- Analizar el APF para sistemas monofásicos y trifásicos.
- Analizar y diseñar una estrategia de modulación para el MPC aplicado al APF.
- Comparar y analizar los resultados teóricos, el desempeño del control con modulación respecto al convencional.

1.3. Organización del documento

El documento se ha organizado en tres partes. En la Parte I se detallan las generalidades del trabajo, se realiza una presentación del mismo, sus fundamentos y demás cuestiones preliminares (Capítulo 1). Posteriormente, se aborda el estado del arte de los APFs, los distintos tipos y las topologías de convertidores comúnmente utilizados dando especial énfasis al APF de dos niveles basado en convertidores Puente-H. Se presenta además las

estrategias de control que se han utilizado para el control de estos convertidores, dando especial énfasis al MPC (Capítulo 2).

En la Parte II se discuten los resultados obtenidos en los trabajos de investigación realizados (Capítulo 3). Posteriormente se exponen las conclusiones alcanzadas y se presentan futuros trabajos en la línea de investigación planteada en la Tesis de Maestría (Capítulo 4).

La Parte III se compone de los tres artículos, desarrollados durante la realización de la presente Tesis de Maestría. El primero se centra en el MPC aplicado APFs de cuatro hilos con carga desbalanceada compensando la potencia reactiva y la corriente del neutro (Artículo 1). Luego se diseña una técnica de modulación que primeramente es aplicado al APF monofásico (Artículo 2), para luego aplicarlo en un sistema trifásico (Artículo 3). Por último, en el Apéndice se adjuntan todos los trabajos realizados en carácter de coautor y los documentos de las actividades desarrolladas durante el periodo de movilidad en la Universidad de Trento, Italia.

CAPÍTULO 2

ESTADO DEL ARTE DEL CONTROL PREDICTIVO APLICADO A LOS APFS

2.1. Introducción

Los sistemas actuales de distribución de CA están enfrentando una serie de problemas de calidad de energía, especialmente debido al uso de equipos sensibles en la mayoría de las aplicaciones industriales, residenciales, comerciales y de tracción [7]. Estos problemas de calidad de energía se clasifican como problemas de tensión y de calidad de corriente en los sistemas de distribución [8].

Los dispositivos de potencia personalizados (DPC), restauradores de voltaje dinámico (DVR), acondicionadores de calidad de energía unificados (UPC) y los compensadores estáticos (STATCOM), se utilizan para mitigar algunos de los problemas dependiendo de los requisitos, en donde el STATCOM es ampliamente utilizado para mitigar los problemas de calidad de energía basados en la corriente, como un factor de potencia deficiente, o una regulación de voltaje deficiente, corrientes desequilibradas y circulación de corriente por el punto neutro [9]. Por lo tanto, dependiendo de los problemas, la configuración del STATCOM se selecciona en la práctica, con el objetivo de mitigar los problemas actuales

de la calidad de energía, especialmente en los sistemas de distribución [10]. Los avances del desarrollo del STATCOM fueron gracias a la evolución de la microelectrónica, a partir del uso de componentes analógicos y digitales discretos, la progresión ha microprocesadores, microcontroladores y DSP (procesadores de señales digitales), ahora es posible implementar complejos algoritmos en línea para el control de STATCOM [11].

La tecnología STATCOM en la actualidad es una tecnología madura para proporcionar compensación de potencia reactiva, balanceo de carga, compensación de la corriente por el punto neutro y compensación de corriente armónica (si es necesario) en redes de distribución de CA, ha evolucionado en el último cuarto de siglo con el desarrollo en términos de configuraciones variables, estrategias de control y dispositivos de estado sólido [12]. Estos dispositivos de compensación también se utilizan para regular el voltaje de terminales, suprime el parpadeo de voltaje y mejora el equilibrio de voltaje en sistemas trifásicos [13]. Estos objetivos se alcanzan individualmente o en combinación dependiendo de los requerimientos y la estrategia de control y configuración que necesitan ser seleccionados apropiadamente [14]-[16]. Esta sección describe el historial de desarrollo y el estado actual de la tecnología STATCOM.

2.2. Tipos de filtros activos

Según los problemas de calidad de energía que se desea solucionar se selecciona el tipo de APF adecuado, los filtros activos se clasifican en cuatro tipos principales como se muestra en la **Figura 2.1** [17] que son; el APF paralelo, que es utilizado para mejorar la corriente eléctrica en la red de distribución, APF en serie, para mejorar la calidad de tensión en la red de distribución, APF híbrido, que es la combinación del APF paralelo y serie, y los acondicionadores de calidad de energía unificado [17], [18].

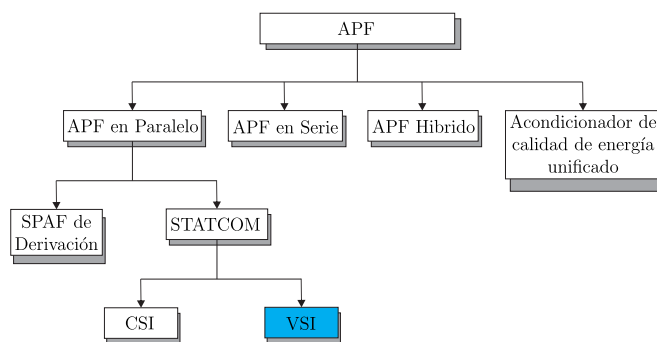


Figura 2.1 Configuraciones de APF para mejorar la calidad de la energía

El APF paralelo puede clasificarse en dos tipos el SPAF y el STATCOM, en donde el SAPF funciona inyectando corriente armónica en el sistema, de magnitudes como las corrientes armónicas generadas por una carga no lineal dada, pero con fases opuestas para mantener una corriente sinusoidal en el PCC [19]. El principal objetivo del SAPF es compensar corrientes armónicas a fin de dar una mejora al factor de potencia [20]. Sin embargo, el STATCOM funciona inyectando corriente en el PCC compensando la potencia reactiva de la carga, mejorando de esta manera el factor de potencia, corrientes desequilibradas y la compensación de la corriente en el punto neutro [21]. La clasificación de convertidores utilizados en el STATCOM son el convertidor de fuente de corriente (CSI) y convertidor de fuente de voltaje el (VSI), en donde el VSI ha demostrado ser más eficiente, tener mayor fiabilidad, una respuesta dinámica más rápida [22]. En esta Tesis de Maestría se ha optado por el APF en modo STATCOM utilizando el convertidor VSI, a continuación se presentan los tipos de convertidores dentro de la configuración VSI.

2.3. Topologías de los convertidores utilizados en filtros activos

Existen varias topologías de convertidores utilizados en los APFs, de los cuales varios trabajos han reportado el uso de la técnica MPC en convertidores de potencia como el punto neutro de fijación de tres niveles (3L-NPC), convertidor de capacitor flotante (FCI), rectificadores frente activo (AFE), convertidores Puente-H (CHB) y los convertidores matriciales (MC) [23]. En la **Figura 2.2** se presenta una taxonomía de las diferentes topologías de convertidores de potencia aplicado a los APFs, donde la topología CHB presenta la ventaja de ser modular respecto a las otras, pudiendo utilizarse en dos niveles o multiniveles [24].

La configuración CHB multinivel presenta varias ventajas con respecto a la de dos niveles, como la serie de estructuras CHB permite un diseño escalable debido a la estructura

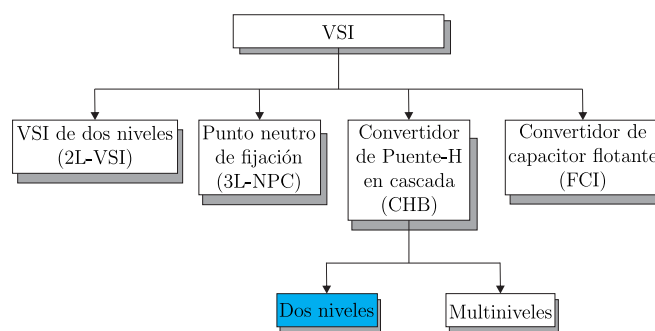


Figura 2.2 Tipos de convertidores aplicados a filtros activos

idéntica de cada CHB, esto permite un proceso de fabricación más rápido y de bajo costo [25]. Requiere un menor número de componentes considerando que no hay diodos extra de sujeción o condensadores de equilibrado de voltaje para lograr el mismo número de niveles de tensión [26]. El potencial de descarga eléctrica se reduce debido a las fuentes DC separadas [27]. Por otro lado se puede mencionar algunas desventajas, tales como se requieren fuentes de DC separadas para cada uno de los CHB [28]. La modulación necesita ser optimizada para aplicaciones de alto rendimiento, debido a una combinación limitada de patrones de conmutación [29]. Para el intercambio de potencia reactiva, el pulso de potencia debe ser el doble de la frecuencia de salida, en consecuencia el DC-link de cada CHB requiere un sobredimensionamiento de los condensadores del DC-link [30]. Cada CHB posee corrientes desiguales y requiere un mayor costo computacional, por mencionar algunos [31].

En esta Tesis de Maestría se ha optado con la configuración CHB de dos niveles, por razones prácticas, ya que tiene un número menor de estados de conmutación, un menor costo computacional, de esta manera se lleva a prueba el algoritmo y propuesta de modulación, para luego extenderlo a multiniveles. A continuación se presenta la principales estrategias de control aplicado a los convertidores.

2.4. Estrategias de control

El control de los convertidores de potencia aplicado a los APFs ha sido ampliamente estudiado, obteniéndose nuevos esquemas de control, entre los que se puede clasificar según la **Figura 2.3**. De éstos, los controles por histéresis y los controles lineales son los más establecidos en la literatura, sin embargo, con el desarrollo de microprocesadores más potentes, la implementación de y esquemas de control más complejos [32]. Algunos de los nuevos esquemas de control para convertidores de potencia son la lógica difusa, control de modo deslizante y el control predictivo [33]. La lógica difusa es adecuado para aplicaciones en las que el sistema controlado o sus parámetros son desconocidos [34]. El modo deslizante presenta robustez y tiene en cuenta la naturaleza de conmutación de

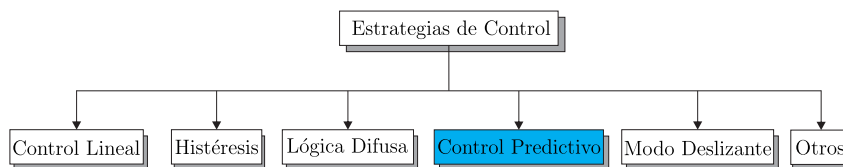


Figura 2.3 Estrategias de control en convertidores

convertidores potencia, otros esquemas de control encontrados en la literatura son redes neuronales, neuro-difuso, y otras técnicas de control avanzados [35]-[37].

El control predictivo presenta varias ventajas que lo hacen adecuados para el control de convertidores de potencia, es intuitivo y fácil de entender, se puede aplicar a una variedad de sistemas, las restricciones y las no linealidades pueden ser fácilmente incluidas [38]. Puede considerarse un caso multivariable, y el controlador es fácil de implementar, requiere una gran cantidad de cálculos, en comparación con un esquema de control clásico; sin embargo, los microprocesadores rápidos disponibles hoy en día es posible implementar del control predictivo [39]. En general, la calidad del controlador depende de la calidad del modelo [40]. El control predictivo constituye una clase muy amplia de controladores que han encontrado una aplicación bastante reciente en convertidores de potencia, la clasificación propuesta en este documento para diferentes controles predictivos se muestra en la **Figura 2.4**. En esta Tesis de Maestría se ha utilizado el MPC como estrategia de control aplicado al APF basado en convertidores en configuración Puente-H de dos niveles.

2.5. Control MPC aplicado al APF

El MPC aplicado a los convertidores toma en cuenta la naturaleza discreta de los convertidores de potencia y los problemas de optimización puede ser simplificado y reducido a las predicciones del comportamiento del sistema para los posibles estados de conmutación, entonces, cada predicción es evaluada en una función de costo y el estado que la minimice es seleccionado [41], [42]. Como se tiene un número de acciones de control finita, este enfoque se denomina MPC de estado finito (FCS-MPC), por su nombre en inglés finite control set MPC o también llamado Direct MPC [43], [44]. Este método es una atractiva alternativa para los métodos de control clásicos en convertidores, debido a su simplicidad, rápida respuesta dinámica, fácil inclusión de no linealidades y restricciones en el diseño del controlador [45], [46]. Más aún, este esquema de control no requiere lazos internos de corriente ni un modulador, lo cual reduce de gran manera la complejidad

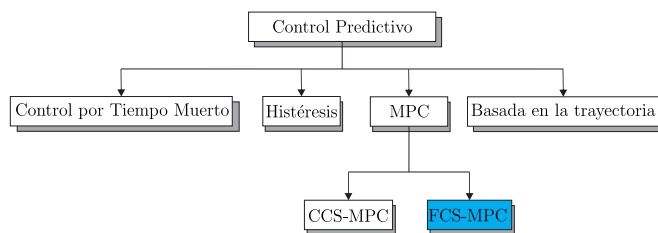


Figura 2.4 Estrategias de control predictivo aplicado a convertidores

de implementación. Esta técnica de control ha sido aplicada en un amplio rango de convertidores como; los de dos niveles trifásicos [47], de tres niveles [48], multifase [49], de capacitor flotante [50], back to back [51], de Puente H en cascada [52], convertidores matriciales [53], entre otros.

Una de las características de MPC es la posibilidad de incluir múltiples objetivos en el diseño del controlador. En los convertidores se puede aplicar al control de corriente, control de voltaje, control de torque y flujo, control de potencia, reducción de frecuencia de conmutación, etc. Para cumplir con la consigna de control deseada, sólo es necesario modificar la función de coste tal como se muestra a continuación.

Control de corriente

Un ejemplo sencillo de control de corriente utilizando FCS-MPC para un convertidor se muestra en la siguiente ecuación, donde la función de costo se define como [54]:

$$g_i = |i^* - i| \quad (2.1)$$

donde i^* es la referencia e i es la predicción de corriente, donde no existen parámetros a ajustar, sin embargo, posee un mayor contenido armónico [55].

Control de tensión

Para la regulación de la tensión del DC-link del convertidor del APF, se puede definir la siguiente función de costo [56]:

$$g_v = |v^* - v| \quad (2.2)$$

donde v^* es la referencia y v es la predicción de voltaje, no existen parámetros a sintonizar. En este caso no se requiere trabajar con un lazo de control de corriente, ya que el voltaje se controla directamente. En general, los problemas de control de voltaje son comunes en convertidores multinivel, donde se requiere que las tensiones en los condensadores sean equilibradas para un mejor rendimiento [57].

Control de Potencia

Este enfoque ha sido llamado control de potencia directa (DPC), el cual realiza un seguimiento para la potencia instantánea activa y reactiva. En se presenta un conversor back to back, o también llamado, AC/DC/AC. En este se propone una función de costo [58]:

$$g_{PQ} = |P^* - P| + |Q^* - Q| \quad (2.3)$$

donde P^* y Q^* son la referencia de la potencia activa y reactiva, respectivamente. P y Q son las predicciones de la potencia activa y reactiva, respectivamente. En este caso, Q es igual a cero y la potencia reactiva se obtiene de un lazo de control del voltaje en el DC-link [59]-[61].

Reducción de frecuencia de conmutación

Algunas aplicaciones en electrónica de potencia requieren reducir la frecuencia de conmutación para minimizar las pérdidas de potencia, en aquellos casos un factor de ponderación puede ser considerado en la función de costo del MPC para tener en cuenta el número de cambios de estado y la frecuencia promedio puede ser reducida con una función de costo que incluye alguna de los criterios anteriores y además la siguiente [60]:

$$g_n = n_c \quad (2.4)$$

donde n_c es el número de conmutaciones del convertidor para alcanzar el siguiente estado [62]. En la presente Tesis de Maestría se ha utilizado el control de corriente como parámetro de control del APF. En la siguiente sección se presenta los parámetros de distorsión armónica que se tienen en cuenta como método de evaluación del rendimiento.

2.6. Parámetros de distorsión armónica

Se utilizan varios parámetros en los sistemas de potencia para caracterizar la distorsión y el contenido armónico de la forma de onda y sus efectos: el THD, DF (factor de distorsión) y CF (factor de cresta). La corriente de carga no lineal i_L se expresa generalmente por [17]:

$$i_L(\theta s) = \sum_{h=1}^{\infty} I_{Lh} \sqrt{2} \sin(h\theta s - \phi_h) = I_{L1} \sqrt{2} \sin(\theta s - \phi_1) + \sum_{h=2}^{\infty} I_{Lh} \sqrt{2} \sin(h\theta s - \phi_h) \quad (2.5)$$

donde: ϕ_1 es el ángulo de fase de la corriente fundamental de carga, $\theta_s = \omega t$, ω es la frecuencia de la red y t el tiempo, I_{L1} es la amplitud rms de la corriente fundamental de carga, I_{Lh} es la amplitud rms de la corriente armónica de carga y ϕ_h es el ángulo de fase de la armónica corriente de carga. La corriente rms total de carga I_{rms} es:

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_{Lh}^2} \quad (2.6)$$

Factor de potencia

La potencia aparente S (voltios-amperios) de un sistema de potencia se da como:

$$S = V_{rms} I_{rms} = V_{rms} \sqrt{\sum_{h=1}^{\infty} I_{Lh}^2} \quad (2.7)$$

donde V_{rms} es la tensión rms de línea, la potencia real, también conocida como potencia activa P , se expresa como:

$$P = V_{rms} I_{L1} \cos \theta_1 \quad (2.8)$$

donde θ_1 es el ángulo entre S y P , la expresión PF incluye el contenido armónico de la corriente es:

$$\text{PF} = \frac{P}{S} = \frac{I_{L1}}{\sqrt{\sum_{h=1}^{\infty} I_{Lh}^2}} \cos \theta_1 \quad (2.9)$$

la potencia reactiva Q en voltios amperios reactivos (VAr) es:

$$Q = V_{rms} I_{L1} \sin \theta_1 \quad (2.10)$$

para estimar la participación de los armónicos en la potencia aparente, se utiliza el concepto de potencia de distorsión D definido como:

$$D = V_{rms} \sqrt{\sum_{h=2}^{\infty} I_{Lh}^2} \quad (2.11)$$

la potencia aparente se puede escribir de la siguiente manera:

$$S = \sqrt{P^2 + Q^2 + D^2} \quad (2.12)$$

por lo tanto, PF puede expresarse como:

$$PF = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \quad (2.13)$$

obsérvese que PF se degrada por la presencia de armónicos y el intercambio de potencia reactiva entre la fuente y la carga [63].

Distorsión armónica total

El THD permite evaluar la diferencia entre la forma de onda real y la de onda sinusoidal de la corriente o la tensión. Se utiliza para cuantificar los niveles de la corriente que fluye en el sistema de distribución o el nivel de voltaje en el PCC donde la empresa puede suministrar a otros clientes. Es definida como la relación de la amplitud rms de armónicos a la amplitud rms de la componente fundamental de la tensión o corriente tal como se da en la siguiente ecuación:

$$THD \% = 100 \frac{\sqrt{\sum_{h=2}^{\infty} I_{Lh}^2}}{I_{L1}} \quad (2.14)$$

al usar el THD que se aplica a la corriente, el PF se convierte en:

$$PF = \frac{\cos \phi_1}{\sqrt{1 + THD^2}} \quad (2.15)$$

Factor de distorsión

El DF se define como la relación entre el valor rms de la corriente fundamental y el valor rms de la misma corriente:

$$DF = \frac{I_{L1}}{I_{rms}} \quad (2.16)$$

cuando la corriente es perfectamente sinusoidal $DF = 1$, ésta disminuye cuando la corriente se distorsiona.

Factor de cresta

Otra cantidad importante que caracteriza la calidad de la fuente de corriente es el CF. El CF es la relación entre los valores de pico y el valor rms total de la misma corriente:

$$CF = \frac{I_{pico}}{I_{rms}} \quad (2.17)$$

para una forma de onda sinusoidal, CF es igual a 1,41. El factor máximo puede alcanzar valores superiores a 4 y 5 para muchas ondas distorsionadas, especialmente para los rectificadores de diodos que alimentan cargas capacitivas.

2.7. Estrategias de modulación

En un VSI, la modulación es el mecanismo empleado para sintetizar la tensión de salida del mismo. La técnica de modulación empleada en el convertidor determina el aprovechamiento de los recursos de tensión de su bus de continua, la calidad y linealidad de la tensión de salida, el rizado de la corriente, las pérdidas de potencia de conmutación, etc. Las técnicas de modulación están enfocadas en la generación de las señales de disparo de las llaves semiconductoras del convertidor a partir de las señales de referencia o consigna obtenidas del algoritmo de control, en términos de tensiones [64].

El control de los convertidores para que establezcan las consignas de control calculadas no es objeto del presente trabajo, por lo tanto, se mencionarán las técnicas de control de corriente para convertidores trifásicos de dos niveles más utilizadas y se presentarán las aplicadas a los modelos implementados. Las más utilizadas son la modulación por ancho de pulso (PWM), el control por histéresis y modulación vectorial espacial (SVM).

El MPC en electrónica de potencia se refiere al método de predecir el comportamiento de la variable de control de tiempo discreto en un convertidor de potencia y luego encontrar el estado de conmutación de salida que minimiza la función de costo [65]. El rendimiento dinámico de las variables de control se mejora porque el MPC selecciona el estado de conmutación de salida óptimo que asegura el mínimo error entre la referencia y la predicción de la variable que se está controlando, en cada período de muestreo [66].

Este trabajo presenta una técnica de modelo de control predictivo aplicado al APF que puede compensar el tiempo de inactividad o no linealidades en el sistema. Además, el MPC proporciona un método de control flexible para diferentes aplicaciones gracias a los avances de los dispositivos de conmutación. Sin embargo, una de las principales desventajas de este método es su naturaleza de frecuencia de conmutación variable. Por ejemplo, el MPC puede elegir solamente de un número limitado de estados de conmutación válidos debido a la ausencia de un modulador. Esto genera armónicos de bajo orden, así

como ruidos en tensión y corriente. La frecuencia de conmutación variable produce un espectro ensanchado, disminuyendo el rendimiento del sistema en términos de calidad de potencia [67].

Se han propuesto diferentes soluciones en la literatura que permiten la operación en conmutación fija frecuencia. El método propuesto emula la implementación de la modulación en el SVM. Como consecuencia, la técnica de modulación por patrón de conmutación propuesto, utiliza un patrón de conmutación con ciclos de trabajo en un tiempo de muestreo dado, a través del esquema de modulación que minimiza la función de coste usando dos vectores activos y cero. Los resultados de la simulación se analizaron para verificar la efectividad del método propuesto.

2.8. Resumen del capítulo

En el presente capítulo se realizó una introducción a la Tesis de Maestría, presentando primeramente los problemas de la calidad de energía actualmente tales como el crecimiento de las cargas no lineales e inductivas y la justificación del uso de los APFs para la mitigación de éstos problemas. Los tipos APFs utilizados, el cual se eligió el APF paralelo en modo STATCOM para compensar la potencia reactiva. Las topologías de convertidores utilizados, el cual se eligió el Puente-H de dos niveles, gracias a su distintas ventajas como ser modular, reducido estados de conmutación, etc. Las distintas técnicas de control aplicado a los convertidores, el cual se optó por el MPC, para luego introduciéndose en detalle la estrategia de control mostrando los objetivos de control aplicado a la función de costo del controlador. Se han analizado los parámetros de distorsión armónica a ser tenidos en cuenta para la mitigación y consecuentemente mejora de la calidad de energía en la red, el cual se ha optado en la compensación de la potencia reactiva y el THD. Se han estudiado las principales técnicas de modulación aplicado a los convertidores de potencia para la reducción del rizado de la inyección del filtro y el THD. La principal contribución de esta Tesis de Maestría es el diseño de un método de modulación con patrón de conmutación aplicado al STATCOM para la compensación de potencia reactiva y reducción del THD del filtro para la mejora de calidad de energía.

Parte II

ANÁLISIS DE CONTENIDO

CAPÍTULO 3

DISCUSIÓN DE LAS APORTACIONES

Las investigaciones realizadas en la presente Tesis de Maestría se centra en el MPC aplicado a los APFs basado en convertidores en configuración Puente-H de dos niveles, donde primeramente se aplica la estrategia de control MPC al APF trifásico de cuatro hilos con carga desbalanceada con el objetivo compensar la potencia reactiva y eliminar la corriente del punto neutro. Posteriormente, debido a que el MPC conmuta a frecuencia de conmutación variable que causa distorsión armónica de bajo orden, así como grandes rizados de tensión y corriente se ha propuesto una estrategia de modulación con patrón de conmutación con el objetivo de obtener una forma de onda modulada a la salida del convertidor. Para ello, se han propuesto métodos de identificación de los parámetros eléctricos, que posteriormente fueron utilizados en el planteamiento del modelo predictivo de corriente aplicado al APF. La estrategia de modulación propuesta ha sido comparada con la convencional, con el objetivo de demostrar su eficiencia y aplicado al APF monofásico y trifásico. Los resultados son obtenidos a través de simulaciones utilizando la herramienta computacional MatLab/Simulink, con lo cual se ha simulado la estrategia de MPC y la modulación propuesta. Posteriormente, los resultados son analizados y

comparados con el método convencional. Se ha aplicado en el APF la compensación de potencia reactiva y la reducción del THD del convertidor. En este capítulo se presenta una breve descripción y discusión de los trabajos de investigación publicados, mostrando las principales contribuciones y aportes obtenidos así como su nexo común. Las discusiones se enfocan en un análisis comparativo de la técnica propuesta con la convencional en las distintas configuraciones monofásico, trifásicos y trifásicos con cuatro hilos, con el fin de destacar el interés de las aportaciones presentadas.

En la sección 3.1 se detalla la aportación realizada en la conferencia Ecuador Technical Chapters Meeting (ETCM2016), del artículo denominado “Model Predictive Current Control with Neutral Current Elimination for H-Bridge Two-Level Active Power Filters”, en el cual se propuso la estrategia de control MPC al APF trifásico de cuatro hilos con carga desbalanceada, el cual se compensó la potencia reactiva y la corriente de neutro utilizando convertidores Puente-H de dos niveles.

En la sección 3.2 se detalla la aportación realizada en la conferencia International Conference On Industrial Engineering and Applications (ICIEA2017), “Modulated Model Predictive Current Control for H-Bridge Two-Level Single Phase Active Power Filters STATCOM”, en el cual se diseñó una estrategia de modulación para el STATCOM, el redujo el THD en el PCC y se comparó con la estrategia MPC convencional.

En la sección 3.3 se detalla el artículo denominado “Modulated Model Predictive Current Control for H-Bridge Two-Level Three Phase Active Power Filters STATCOM”, que actualmente se encuentra en proceso de redacción, en el cual el diseño de modulación anterior se extiende a sistemas trifásicos, reduciendo el THD en el PCC y comparando con la estrategia MPC convencional.

3.1. Control MPC aplicado al APF trifásico de cuatro hilos

En el siguiente artículo se presenta la propuesta de control MPC aplicado al APF para sistemas trifásicos de cuatro hilos basado en convertidores Puente-H de dos niveles. En la **Figura 3.1** (a) muestra la propuesta de un APF trifásico de cuatro hilos dos niveles con convertidores Puente-H en cascada, que consiste en celdas Puente-H por fase, las diferentes celdas de Puente-H tienen un DC-link independiente (C_{DC}), cada celda contiene cuatro dispositivos de conmutación, dando como resultado un total de 16 conmutadores de potencia, en consecuencia, se necesitan cuatro señales de conmutación (S_{fij}) para controlar cada celda, donde f representa la fase (a, b, c y n), el dispositivo de conmutación correspondiente a la celda (1, 2, 3 o 4) y j el número de la celda en la fase correspondiente (1, 2, 3 o 4), respectivamente. La **Tabla 3.1** muestra las combinaciones permitidas de las señales de activación y los respectivos voltajes de salida correspondientes a la Celda₁

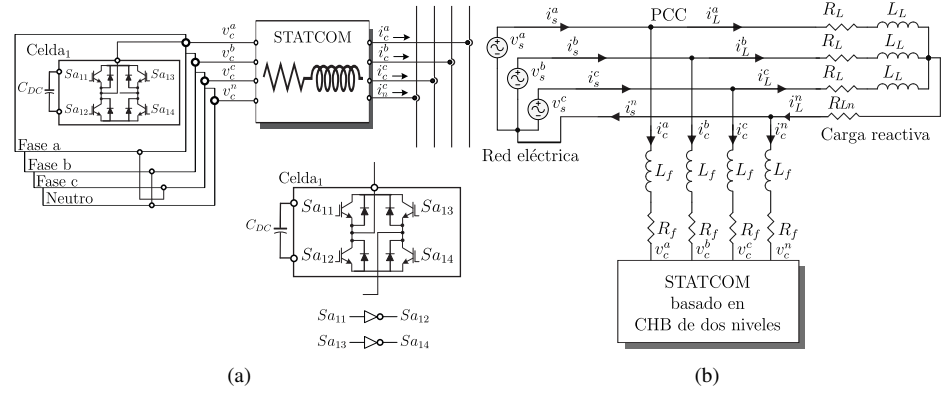


Figura 3.1 APF trifásico de cuatro hilos de dos niveles en configuración Puente-H. (a) APF basado en convertidores Puente-H. (b) Esquema eléctrico del APF trifásico de cuatro hilos

Tabla 3.1 Combinaciones de las señales de activación

S_{a11}	S_{a13}	S_{a12}	S_{a14}	v_c^a
1	0	0	1	$+v_{DC}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-v_{DC}$

de la fase a , donde v_{DC} es el voltaje del condensador, las combinaciones permitidas son similares para las otras celdas, no se permiten otras combinaciones posibles porque causan un cortocircuito en el DC-link de la celda, para evitar esto, sólo se usan dos señales de activación y niveles complementarios como se muestra en la **Figura 3.1** (a) para el caso particular de Celda₁. El modelo dinámico de la configuración del circuito de la **Figura 3.1** (b) puede obtenerse usando las leyes de circuito de Kirchhoff, para fines de modelado, se supone que las fuentes de tensión trifásicas están equilibradas, produciéndose el desequilibrio a los 0.04 s en la fase a aumentando $2R_L$ y que todos los módulos tienen la misma capacitancia y voltaje en su lado de CC. El APF de Puente-H de dos niveles está conectado en el PCC, aplicando la ley de voltaje de Kirchhoff para el lado AC del APF basado en Puente-H, se obtiene la ecuación diferencial que modela el sistema:

$$\frac{di_c^{abcn}}{dt} = \frac{v_s^{abcn}}{L_f} - \frac{v_c^{abcn}}{L_f} - \frac{R_f i_c^{abcn}}{L_f} \quad (3.1)$$

El modelo predictivo se obtiene utilizando el método de discretización de Euler a partir del modelo de dominio de tiempo continuo representado por (3.1), que se obtiene en la ecuación siguiente:

$$i_c^{abcn}(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abcn}(k) + \frac{T_s}{L_f} \{v_s^{abcn}(k) - v_c^{abcn}(k)\} \quad (3.2)$$

donde k es la muestra de tiempo discreto real, T_s es el tiempo de muestreo y $i_c^{abcn}(k+1)$ son una predicción de las corrientes de las fases a, b, c y del punto neutro n en caso que existiese desbalanceo de carga del APF hechas en la muestra k . En el control propuesto calcula los errores previstos para cada vector de voltaje posible como:

$$ei_c^{abcn}(k+1) = i_c^{abcn*}(k+1) - i_c^{abcn}(k+1) \quad (3.3)$$

siendo ei_c^{abcn} los errores actuales de APF en el lado AC, respectivamente. Para cada uno de ellos se evalúa una función de costo, la función de costo se define típicamente como la medida cuadrática del error predicho, que puede definirse como:

$$(g+1) = \|ei_c^{abcn}(k+1)\|^2 \quad (3.4)$$

para la generación de la corriente de referencia se utiliza las transformadas Clark en el marco de referencia $\alpha - \beta - 0$, utilizando la siguiente matriz de transformación:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (3.5)$$

aplicando (3.5), las referencias de corriente $\alpha - \beta - 0$ en el lado AC del APF se obtienen:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (3.6)$$

resolviendo i_{c0}^* queda como:

$$i_{c0}^* = i_{L0} \quad (3.7)$$

donde el exponente (*) denota las variables de referencia y P_c^*, Q_c^* son las referencias de potencia instantánea activa, reactiva y P_{C0}^* es la potencia instantánea de secuencia cero, respectivamente. En la **Figura 3.2** muestra el esquema propuesto de la técnica de control

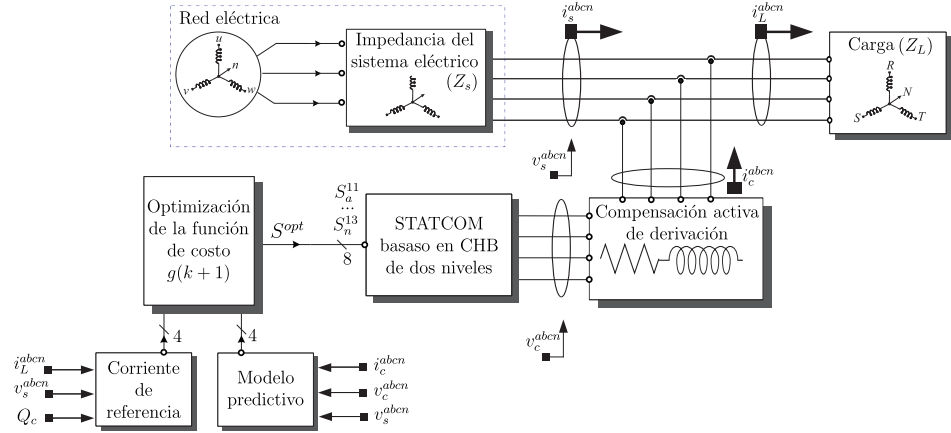


Figura 3.2 Diagrama en bloque del control APF trifásico cuatro hilos

MPC de corriente aplicada al sistema APF trifásico de cuatro hilos en configuración Puente-H de dos niveles, la estrategia de control propuesta utiliza una frecuencia de conmutación variable y una frecuencia de muestreo f_m de 40 kHz y una tensión del DC-link de 342 V, el algoritmo que minimiza la función de costo y los parámetros eléctricos se presentan en el capítulo 5, respectivamente. Considerando que el APF opera con carga balanceada y ocurriendo el desbalanceo de carga a los 0.04 s en la fase a de la carga, considerando un aumento de $2R_L^a$, los resultados de simulación obtenidos del MPC aplicado al APF trifásico de cuatro hilos basados en convertidores Puente-H de dos niveles se muestra en la **Figura 3.3** (a), la potencia activa P_s y reactiva Q_s en el lado de la red (arriba), se puede observar que P_s permanece constante de 4 kW y Q_s un valor promedio de cero, compensando la potencia reactiva en la red eléctrica, también se pueden observar las corrientes i_L^a , i_s^a y i_c^a (abajo) en respuesta transitoria.

En la **Figura 3.3** (b), se observa la dinámica del sistema, cuando ocurre el desbalanceo de carga se genera la circulación de la corriente en el punto neutro i_L^n , la corriente inyectada i_c^n y la referencia i_c^{n*} del APF. Cuando se produce el desequilibrio de carga, la corriente inyectada por el APF y la corriente neutra de la carga 180 grados para compensación de la corriente por el punto neutro, se puede observar que la corriente neutra de la fuente i_s^n es en promedio aproximadamente cero, que cumple con los parámetros de cálculo y diseño del APF. En conclusión, se obtuvo una compensación simultánea de la potencia reactiva y de la circulación de la corriente del punto neutro, logrando una disminución del 79 % de la potencia reactiva, de 3018 VAR a 631 VAR rms y una reducción del 59 % de la corriente del punto neutro, de 3.46 A a 1.41 A en rms.

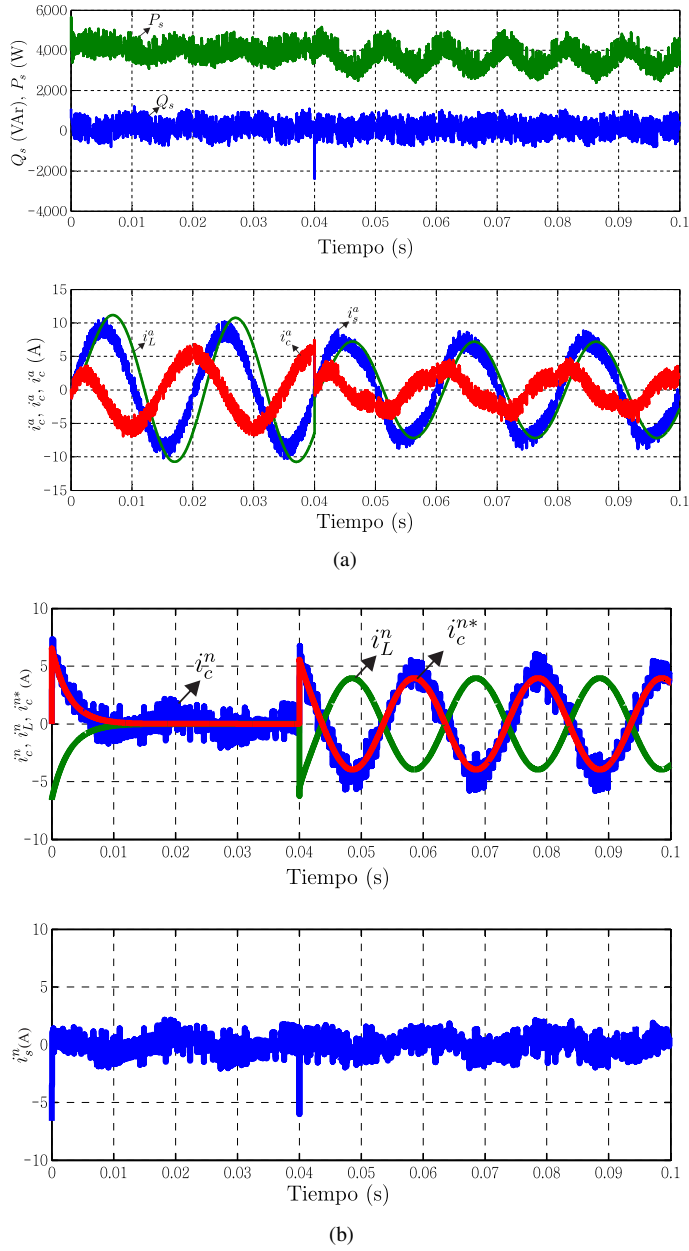


Figura 3.3 Resultados teóricos de la aportación 1. (a) Respuesta transitoria APF de dos niveles CHB, compensación de potencia reactiva. (b) Respuesta transitoria APF de dos niveles CHB, compensación de la corriente del neutro

3.2. Control MPC modulado aplicado al APF monofásico

Debido a que la estrategia de control MPC opera a una frecuencia de conmutación variable y solo puede seleccionar un número limitado de estados de conmutación válidos, debido a la ausencia de un modulador, esto genera armónicos de bajo orden, así como grandes rizados en la tensión y corriente, con una propagación del espectro, disminuyendo el rendimiento del sistema en términos de la calidad de potencia. En esta sección se presenta la segunda aportación de esta Tesis, que se constituye en una estrategia de modulación para el MPC aplicado al APF monofásico primeramente, para luego extender la estrategia a sistemas trifásicos. El esquema eléctrico se muestra en la **Figura 3.4** en donde v_s^a e i_s^a representan la tensión y la corriente de la red eléctrica en la fase a , respectivamente, R_L , L_L representan la carga e i_L^a consumida por la corriente de la carga y finalmente i_c^a , v_c^a son la corriente inyectada por el APF y la tensión del DC-link representado por C_{DC} , la celda Puente-H contiene un DC-link y cuatro dispositivos de conmutación, en consecuencia cuatro señales de activación de los cuales se utilizan dos S_{a11} , S_{a13} y sus complementarios S_{a12} , S_{a14} . A la salida del convertidor se encuentra el filtro pasivo R_f y L_f . El APF de Puente-H de dos niveles está conectado al PCC, aplicando la ley de voltaje de Kirchhoff para el lado AC del APF basado en Puente-H, se obtiene la ecuación diferencial que modela el sistema:

$$\frac{di_c^a}{dt} = \frac{v_s^a}{L_f} - \frac{v_c^a}{L_f} - \frac{R_f i_c^a}{L_f} \quad (3.8)$$

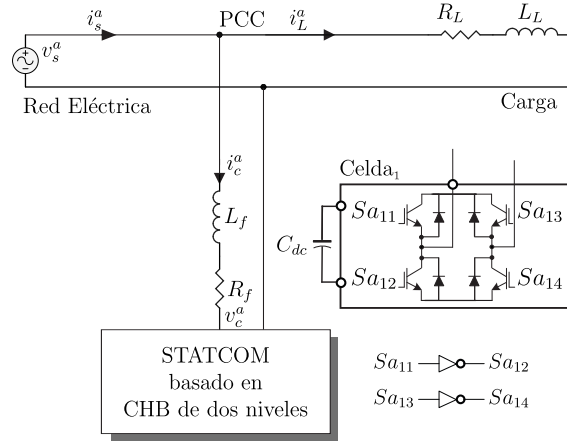


Figura 3.4 Esquema eléctrico del APF monofásico basado en convertidores Puente-H

El modelo predictivo se obtiene utilizando el método de discretización de Euler a partir del modelo de dominio de tiempo continuo representado por (3.8), que se obtiene en la ecuación siguiente:

$$i_c^a(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^a(k) + \frac{T_s}{L_f} \{v_s^a(k) - v_c^a(k)\} \quad (3.9)$$

donde k es la muestra de tiempo discreto real, T_s es el tiempo de muestreo y $i_c^a(k+1)$ es la predicción de la corriente de la fase a del APF hechas en la muestra k . En el control propuesto calcula los errores previstos para cada vector de voltaje posible como:

$$ei_c^a(k+1) = i_c^{a*}(k+1) - i_c^a(k+1) \quad (3.10)$$

siendo ei_c^a es el error actual de la corriente del APF en el lado AC, respectivamente, evaluando la función de costo como la medida cuadrática del error predicho:

$$g(k+1) = \| ei_c^a(k+1) \|^2 \quad (3.11)$$

para la generación de la corriente de referencia se utiliza el triangulo de potencia como se muestra en la **Figura 3.5**, (a) S , Q , P y ϕ , representan la potencia aparente, la potencia reactiva, la potencia activa y el ángulo entre S y P , (b) la corriente i_L^a se proyecta en los ejes de coordenadas i_L^{ax} e i_L^{ay} , (c) se utiliza las mediciones de la amplitud de la corriente

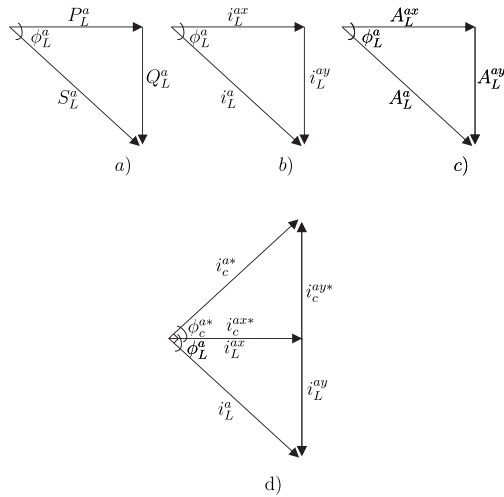


Figura 3.5 Generación de la referencia. (a) Triangulo de potencia de la carga. (b) Proyección de la corriente de carga en los ejes de coordenadas, (c) Proyección de la amplitud de la corriente de carga en los ejes de coordenadas. (d) Corriente de referencia proyectado en los ejes de coordenadas

de la carga A_L^a , la fase de la corriente de la carga ϕ_L^a y la tensión de la red eléctrica v_s^a a través de un Bucle cerrado de fase (PLL), (d) la corriente de referencia queda como:

$$A_L^{ay} = A_L^a * \sin(\phi_L^a) \quad (3.12)$$

luego se aplica el vector de referencia para compensar el componente reactiva de la corriente medida y por lo tanto la potencia reactiva, como se muestra en la **Figura 3.5** (d):

$$i_L^{ay*} = A_L^{ay} * \sin(\omega t - \pi/2) \quad (3.13)$$

El esquema de control y modulación se muestra en la **Figura 3.6**, la propuesta de modulación utiliza la **Tabla 3.1**, donde es posible definir los dos vectores activos $v_1 = +v_{DC}$ y $v_2 = -v_{DC}$ que corresponden a la tensión generada por el estado de conmutación, respectivamente, el método propuesto se muestra en cada vector disponible para el CHB, con la misma idea que el método clásico de control predictivo ya que utiliza la misma predicción de la corriente de carga.

Además, la técnica propuesta evalúa la predicción de los dos vectores activos en cada momento de muestreo y evalúa la función de costo por separado para cada predicción. La función de costo g se evalúa para cada caso y es la misma como la considerada para el método predictivo clásico (3.9). Por ejemplo, para la primera predicción, se evalúa la función de costo g_1 para el vector v_1 y la segunda predicción y la función de costo g_2 se evalúa para el vector v_2 , cada predicción es evaluado y el único cambio es al respecto del cálculo de la tensión de carga v_L^a , los ciclos de trabajo se calculan resolviendo:

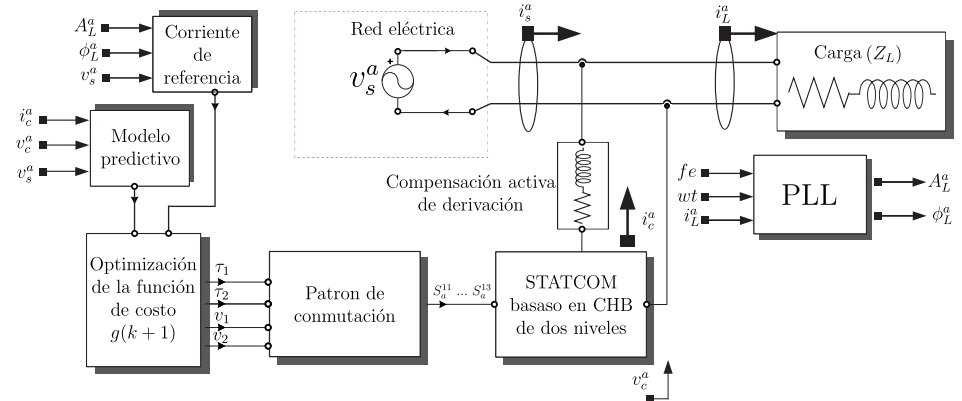


Figura 3.6 Diagrama en bloque del control APF monofásico

$$\begin{aligned}
\tau_1 &= \frac{K}{g_1} \\
\tau_2 &= \frac{K}{g_2} \\
\tau_1 + \tau_2 &= T_s
\end{aligned} \tag{3.14}$$

resolviendo la ecuación (3.14), es posible obtener la expresión para K y las expresiones para los ciclos de trabajo para cada vector τ_1 y τ_2 respectivamente, posteriormente se calcula una nueva función de costo que se evalúa en cada tiempo de muestreo que se dan como:

$$\begin{aligned}
\tau_1 &= \frac{g_2}{g_1 + g_2} \\
\tau_2 &= \frac{g_1}{g_1 + g_2} \\
g(k+1) &= \tau_1 * g_1 + \tau_2 * g_2
\end{aligned} \tag{3.15}$$

los dos vectores que minimizan esta función de costo se seleccionan y se aplica al CHB en el siguiente momento de muestreo, luego se realiza el calculo de los ciclos de trabajo y la selección de los dos vectores óptimos, para finalmente aplicar un procedimiento de patrón de conmutación, tal como el que se muestra en la **Figura 3.7**, con el objetivo de aplicar la dos vectores activos, el algoritmo de control y los parámetros de eléctricos se presentan en el capítulo 6 del correspondiente artículo. Los resultados de simulación obtenidos del MPC aplicado al APF monofásico basado en convertidor Puente-H de dos niveles se muestra en la **Figura 3.8** (superior) se observa la potencia activa $P_L = 1325$ (W) y reactiva $Q_L = 994$ (VAr) en la carga, en la **Figura 3.8** (inferior), se observa la potencia activa $P_s = 1206$ (W) y reactiva $Q_s = -1$ (VAr) en la red eléctrica. Por otra parte, en la **Figura 3.9** (a) muestra la medición de tensión v_a^c a la salida del convertidor, la medición

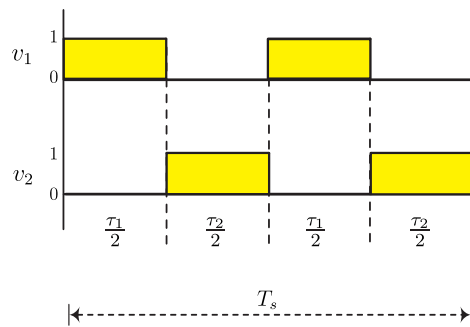


Figura 3.7 Patrón de conmutación

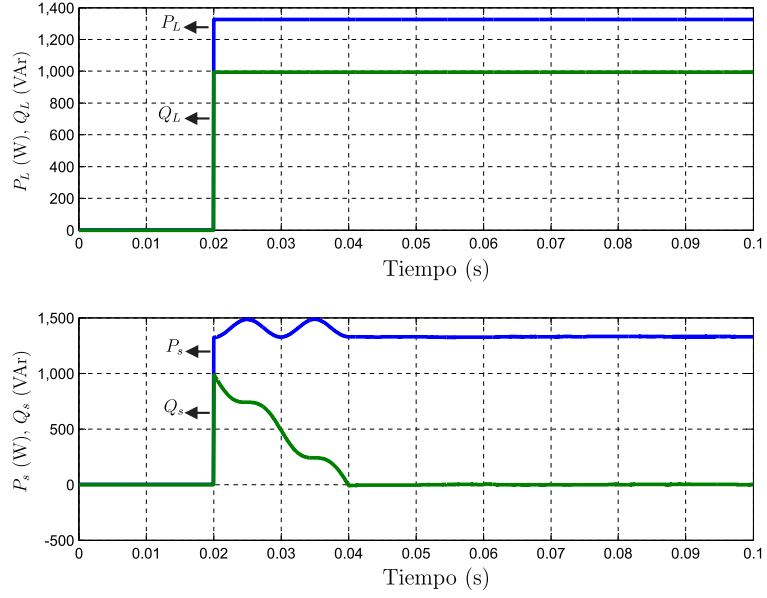


Figura 3.8 Respuesta transitoria del STATCOM compensando la potencia reactiva

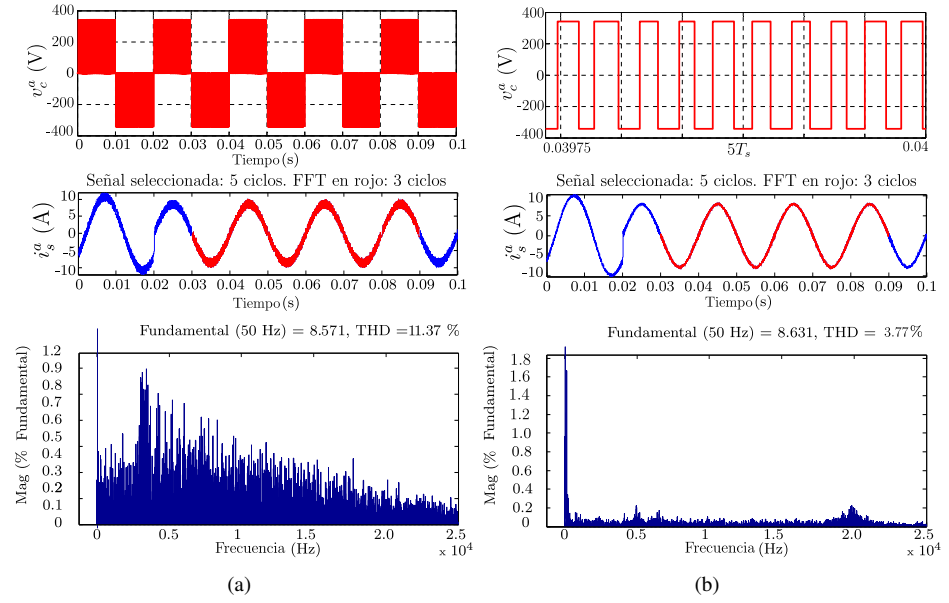


Figura 3.9 Resultados teóricos de la aportación 2. (a) Respuesta transitoria del MPC Clásico. (b) Respuesta transitoria del MPC con modulación

de la corriente i_s^a del lado de la red eléctrica y el análisis del espectro de la corriente i_s^a en términos de THD, utilizando el método MPC clásico, en la **Figura 3.9 (b)**, muestra la medición de tensión a la salida del convertidor v_s^a con un periodo de $5T_s$ donde T_s es el tiempo de muestreo, muestra la medición de la corriente i_s^a y el análisis del espectro en términos de THD, utilizando el MPC con el método de modulación propuesto. Los aportes de este método de modulación son la reducción del efecto de rizado de la corriente a la salida del convertidor, con mejora obtenida en el parámetro de rendimiento THD de aproximadamente el 7.6 % (una caída del 11,37 % al 3,77 %) utilizando el método de modulación por patrón de conmutación.

3.3. Control MPC modulado aplicado al APF trifásico

En esta sección presenta un modelo extendido de la modulación propuesta en sistemas monofásicos, aplicado a sistemas trifásicos con carga balanceada, utilizando el MPC aplicado al APF trifásico basado en convertidores CHB de dos niveles como se muestra en la **Figura 3.10 (a)** la propuesta de un APF trifásico en configuración Puente-H de dos niveles, que consiste en celdas Puente-H por fase, las diferentes celdas de Puente-H tienen un DC-link independiente (C_{DC}), cada celda contiene cuatro dispositivos de conmutación, dando como resultado un total de 8 conmutadores de potencia, en consecuencia, se necesitan cuatro señales de conmutación (S_{fij}) para controlar cada celda, donde f representa la fase (a, b, c , el dispositivo de conmutación correspondiente a la celda (1, 2, 3) y j el número de la celda en la fase correspondiente 1, 2, 3), respectivamente.

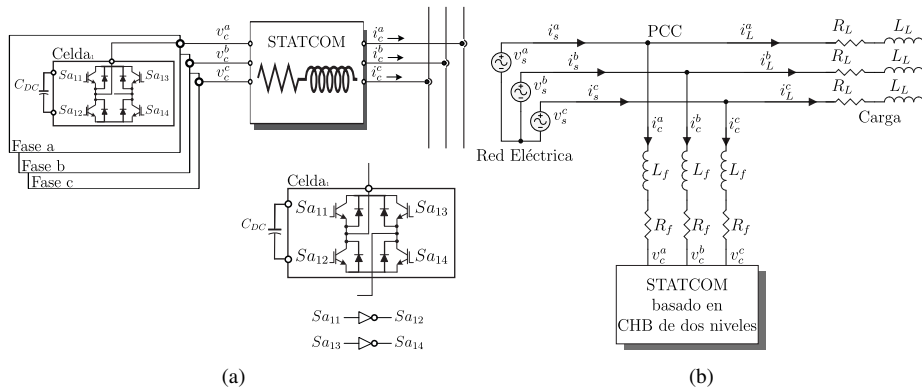


Figura 3.10 APF trifásico configuración Puente-H de dos niveles. (a) APF trifásico basado en CHB de dos niveles. (b) Conexión del APF basado en CHB

La **Tabla 3.1** muestra las combinaciones permitidas de las señales de activación y los respectivos voltajes de salida correspondientes a la Celda₁ de la fase *a*, donde v_{DC} es el voltaje del condensador, las combinaciones permitidas son similares para las otras celdas, no se permiten otras combinaciones posibles porque causan un cortocircuito en el DC-link de la celda, para evitar esto, sólo se usan dos señales de activación y niveles complementarios como se muestra en la **Figura 3.10** (a) para el caso particular de Celda₁.

El modelo dinámico del APF de la **Figura 3.10** (b) puede obtenerse usando las leyes de circuito de Kirchhoff, para fines de modelado, se supone que las fuentes de tensión trifásicas están equilibradas y que todos los módulos tienen la misma capacitancia y voltaje en su lado de CC. El APF de Puente-H de dos niveles está conectado en el PCC, aplicando la ley de voltaje de Kirchhoff para el lado AC del APF basado en Puente-H, se obtiene la ecuación diferencial que modela el sistema:

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{v_c^{abc}}{L_f} - \frac{R_f i_c^{abc}}{L_f} \quad (3.16)$$

el modelo predictivo se obtiene utilizando el método de discretización de Euler a partir del modelo de dominio de tiempo continuo representado por (3.16), que se obtiene en la ecuación siguiente:

$$i_c^{abc}(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}(k) + \frac{T_s}{L_f} \{v_s^{abc}(k) - v_c^{abc}(k)\} \quad (3.17)$$

donde k es la muestra de tiempo discreto real, T_s es el tiempo de muestreo y $i_c^{abc}(k+1)$ son una predicción de las corrientes de las fases *a*, *b* *c* del APF hechas en la muestra k . En el control propuesto calcula los errores previstos para cada vector de voltaje posible como:

$$ei_c^{abc}(k+1) = i_c^{abc*}(k+1) - i_c^{abc}(k+1) \quad (3.18)$$

siendo ei_c^{abc} los errores actuales de APF en el lado AC, respectivamente. Para cada uno de ellos se evalúa la función de costo como la medida cuadrática del error predicho, que se define como:

$$(g+1) = \| ei_c^{abc}(k+1) \|^2 \quad (3.19)$$

para la generación de la corriente de referencia se utiliza las transformadas Clark en el marco de referencia $\alpha - \beta$, utilizando la siguiente matriz de transformación:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (3.20)$$

aplicando (3.20), las referencias de corriente $\alpha - \beta$ en el lado AC del APF se obtienen:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (3.21)$$

donde el exponente (*) denota las variables de referencia y P_c^* , Q_c^* son las referencias de potencia instantánea activa, reactiva, respectivamente. En la **Figura 3.11** muestra el esquema propuesto de la técnica de control MPC de corriente aplicada al sistema APF trifásico en configuración Puente-H de dos niveles, utilizando el mismo método de modulación detallado en la sección anterior se evalúa para sistemas trifásicos. La estrategia de control con modulación propuesta utiliza una frecuencia de muestreo f_m de 40 kHz y una tensión del DC-link de 342 V, el algoritmo que minimiza la función de costo y los parámetros eléctricos se presentan en el capítulo 7, correspondiente al artículo respectivamente. Considerando que el APF se conecta a los 0.02 s en el punto PCC, los resultados de simulación obtenidos del MPC aplicado al APF trifásico basado en convertidores Puente-H de dos niveles se muestra en la **Figura 3.12** (superior), la potencia

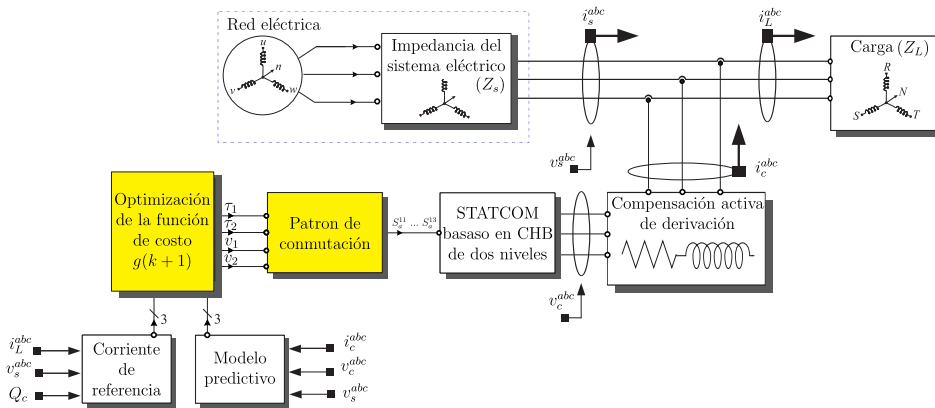


Figura 3.11 Diagrama en bloque del esquema de control propuesto para sistema trifásico

activa $P_L = 3976$ W y reactiva $Q_L = 2982$ VAr de la carga, en la **Figura 3.12** (inferior) se observa la potencia activa $P_s = 3976$ W y reactiva $Q_s = 2982$ VAr correspondiente a la red eléctrica respectivamente, se puede observar una compensación de Q_s del 96 %, 2875 VAr (2982 VAr a 107 VAr) en rms. Por otra parte, los resultados de este método de modulación por patrón de conmutación son la reducción del rizado de la corriente a la salida del convertidor utilizando como parámetro de distorsión armónica el THD, como se muestra en la **Figura 3.13** donde se observa un análisis comparativo del MPC clásico con el MPC modulado, en la **Figura 3.13** (a) se observa las mediciones de la tensión v_c^a a la salida del convertidor, la corriente i_s^a de la red eléctrica y el análisis de THD de la corriente i_s^a utilizando el método de control MPC clásico. En la **Figura 3.13** (b), se observa las mediciones de tensión v_c^a considerando cuatro periodos de muestreo, la medición de la corriente i_s^a y el análisis de THD de la corriente i_s^a utilizando el método de control MPC modulado. Un mejor rendimiento se obtiene utilizando el método de modulación por patrón de conmutación propuesto principalmente en términos de THD menor, debido a los patrones de tiempos asociada con el proceso de modulación, produciendo un espectral discreto y bien definido en contraste con el método MPC clásico. La mejora obtenida en el parámetro de rendimiento THD es de aproximadamente el 7 % (una caída del 9,81 % al 2,82 %) utilizando el método modulación por patrón de conmutación, considerando el intervalo de compensación de la potencia reactiva (después de 0,02 s).

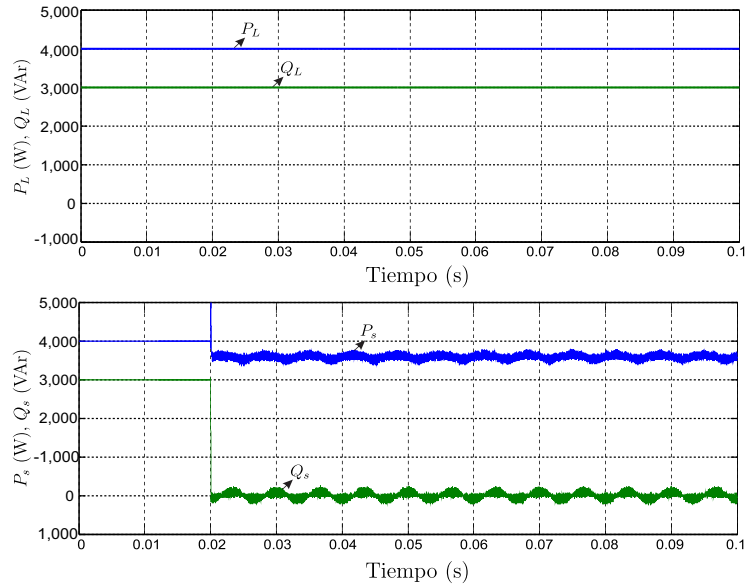


Figura 3.12 Respuesta transitoria del STATCOM compensando la potencia reactiva.

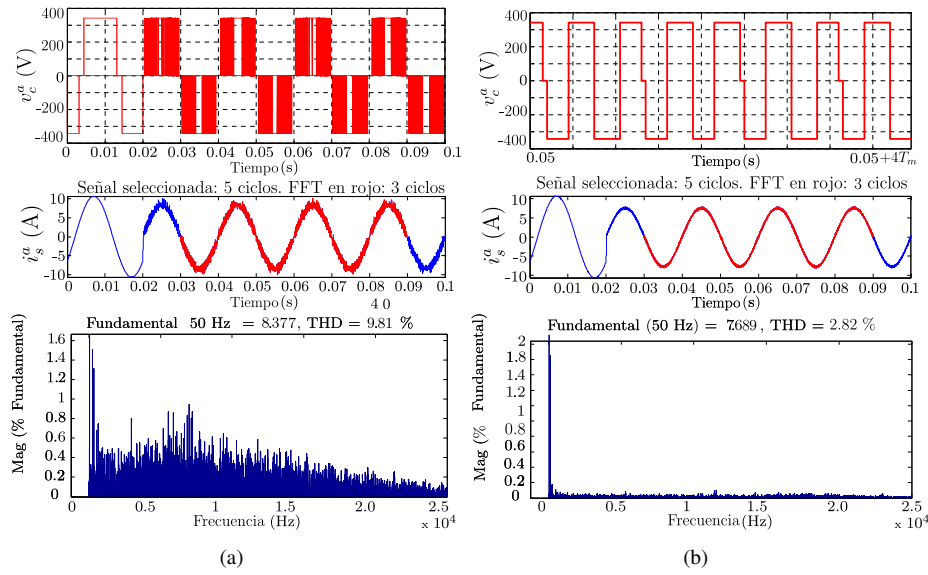


Figura 3.13 Resultados teóricos de la aportación 3. (a) Respuesta transitoria del MPC clásico. (b) Respuesta transitoria del MPC con modulación.

3.4. Conclusiones del capítulo

En el presente capítulo se han presentado la discusión de las aportaciones en los distintos trabajos realizados. Primeramente se presenta el esquema de control y resultado teórico de simulación del control MPC clásico aplicado APF trifásico de cuatro hilos en configuración Puente-H de dos niveles con carga desbalanceada, los resultados de simulación confirman la validez del método de control MPC aplicado al APF, es cual es capaz de compensar la potencia reactiva y la corriente circulante del punto neutro. Sin embargo, Debido a que la estrategia de control MPC opera a una frecuencia de conmutación variable y solo puede seleccionar un número limitado de estados de conmutación válidos, debido a la ausencia de un modulador, esto genera armónicos de bajo orden, así como grandes rizados en la tensión y corriente, con una propagación del espectro, disminuyendo el rendimiento del sistema en términos de la calidad de potencia, debido a esto se diseñó un método de modulación que se presentó en el siguiente aporte.

En el siguiente trabajo se presentó una estrategia de control MPC con una etapa de modulación aplicado al APF monofásico en configuración Puente-H de dos niveles, la estrategia de modulación utiliza patrones de conmutación con un ciclo de trabajo determinado, conservando las mismas ventajas del control MPC clásico como respuesta

dinámica rápida y fácil inclusión de no linealidades. Como resultado se logra compensar la potencia reactiva y además se reduce el rizado de corriente inyectada a la red eléctrica, disminuyendo la propagación del espectro THD, mejorando el rendimiento del sistema en términos de calidad de potencia y mejora de la calidad de energía en la red eléctrica. Y finalmente en el tercer trabajo se presentó el método de modulación extendida para sistemas trifásicos en el cual se compensa la potencia reactiva y se reduce el THD. Los resultados obtenidos han dado lugar a varias publicaciones en congresos de relevancia internacional, los cuales se presentan en la Parte III de la Tesis de Maestría.

CAPÍTULO 4

CONCLUSIÓN Y TRABAJO FUTURO

4.1. Conclusión

Las principales conclusiones obtenidas con el desarrollo de este trabajo son las siguientes:

- Se ha propuesto y analizado una técnica de control predictivo de corriente para un APF de Puente-H de dos niveles. Se ha demostrado que es posible compensar la potencia reactiva instantánea y la corriente circulante por el punto neutro en carga desequilibrada para mejorar el factor de potencia de la red. Los resultados de la simulación confirman la capacidad de la técnica propuesta en el campo de la compensación instantánea de la potencia reactiva y la corriente del neutro para carga desequilibrada.
- Se ha estudiado e implementado una estrategia de control MPC con una etapa de modulación, como un método alternativo a los métodos existentes aplicado al convertidor CHB STATCOM, primeramente para sistemas monofásicos de dos niveles con una modulación por patrón de conmutación, manteniendo las ventajas del modelo

clásico de técnicas de control predictivo tales como respuesta dinámica rápida y fácil inclusión de no linealidades. Los resultados de la simulación, confirman la capacidad de la técnica de modulación por patrón de conmutación propuesta, para la compensación de potencia reactiva instantánea y el rizado de la corriente de salida del convertidor.

- Los resultados obtenidos han dado varios artículos en en conferencias y el libro de Tesis. La **Tabla 4.1** contiene un resumen de los trabajos realizados.

Producción/Actividad	Número
Artículos de conferencia	7
Presentación de trabajos a nivel internacional	1
Participación en proyectos de I+D	1
Revisión de artículos científicos	2
Realización de estancia de investigación	1

Tabla 4.1 Resumen de los logros obtenidos durante la Tesis de Maestría

4.2. Trabajos futuros

- Extender el método de modulación para sistemas trifásicos de cuatro hilos con desbalanceo de carga.
- Extender el método de modulación para sistemas con cargas no lineales.
- Validar el método propuesto en pruebas experimentales.

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Parte III

PUBLICACIONES

CAPÍTULO 5

ARTICULO 1: MODEL PREDICTIVE CURRENT CONTROL WITH NEUTRAL CURRENT ELIMINATION FOR H-BRIDGE TWO-LEVEL ACTIVE POWER FILTERS

Abstract

In this paper, a scheme for reactive power compensation and neutral current elimination based on model predictive control strategy is proposed. In this context, a H-bridge four-wire two-level active power filter is presented. The main feature of the proposed method focuses on the compensation of reactive power and neutral current elimination for unbalanced load in order to improve the power factor. This approach predicts the future behavior of the control actions considering all possible switching states. The proposed method selects the optimal switching vector by using an optimization process considering a defined cost function. The effectiveness of the proposed control approach is evaluated through simulations.

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Introduction

In the last decades, the use of electronic-based power loads increased greatly and consequently the contamination of the distribution systems. In order to solve the various problems of power quality in distribution systems, active power filters (APF) and multilevel static synchronous compensators (M-STATCOM) are considered one of the best and the most popular solution [1]. The purpose of using a four-wire APF, is to perform the suppression of harmonic current, reactive power compensation, power factor correction and neutral current elimination [2], [3]. This can be achieved by the injection of currents at the point of common coupling (PCC) [4]. This type of APF usually requires four H-bridge voltage source inverters (VSI) which provides neutral current through the fourth H-bridge [5], or three H-bridge VSI with star configuration and accessible neutral-wire [6].

As main contribution, and complementing previous works, i.e. [7], a method for power compensation and neutral current elimination applied to a three-phase four-wire H-bridge two-level APF is proposed by using predictive current control. Predictive model is obtained from the dynamic equations of the compensation system. Simulation results have been analyzed in order to verify the effectiveness of the proposed method.

This paper is organized as follows: Section II describes the three-phase four-wire H-bridge APF topology. Section III discusses the proposed model-based predictive control (MPC) strategy. Section IV discusses the effectiveness of the proposed method considering the simulation results. Finally, concluding remarks are summarized in Section V.

Three-phase four-wire H-bridge APF topology

Figura 5.1 shows the proposed three-phase four-wire two-level H-bridge APF topology, consisting in one H-bridge cells per phase. The different H-bridge cells have an independent DC-link (C_{dc}). Each cell contains four switching devices, resulting in a total of 16 power switchers. Consequently, four switching signals (S_{fij}) are needed in order to controlled each cell, where f represents the phase (a , b , c and n), i the cell number in the corresponding phase (1, 2, 3 or 4) and j the switching device corresponding to the cell (1, 2, 3 or 4), respectively.

Table 5.1 shows the allowed combinations of activation signals and the respective output voltages corresponding to the Cell₁ of the phase “a”, where v_{dc} is the voltage of the capacitor. Similar allowed combinations are defined for the other cells. Other possible combinations are not permitted because they cause a short circuit in the DC-link of the cell. To avoid this, only two activation signals and they complementary levels are used as shown in **Figura 5.1** for the particular case of Cell₁.

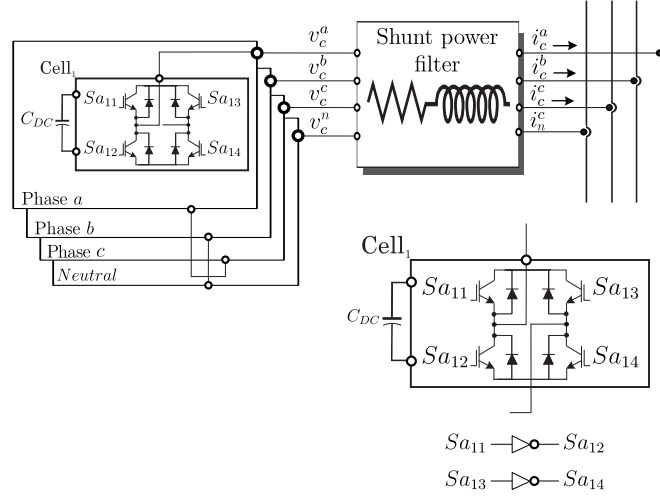


Figure 5.1 Three-phase four-wire two-level H-bridge APF

Two-level H-bridge APF model

The dynamic model of the circuit configuration (**Figure 5.2**) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the three-phase voltage sources are balanced and all modules have the same capacitance and voltage in their DC side. The two-level H-bridge APF is connected at the PCC. Applying Kirchhoff's voltage law for the AC side of the APF, the following equations are obtained:

$$\frac{di_c^{abcn}}{dt} = \frac{v_s^{abcn}}{L_f} - \frac{R_f}{L_f} i_c^{abcn} - \frac{n_c S_{fij} v_{dc}^{abcn}}{L_f} \quad (5.1)$$

$$\frac{dv_{dc}^{abcn}}{dt} = \frac{S_{fij} i_c^{abcn}}{C_{dc}} - \frac{v_{dc}^{abcn}}{R_{dc} C_{dc}} \quad (5.2)$$

Table 5.1 Allowed combinations of activation signals

Sa_{11}	Sa_{13}	Sa_{12}	Sa_{14}	v_c^a
1	0	0	1	$+v_{dc}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-v_{dc}$

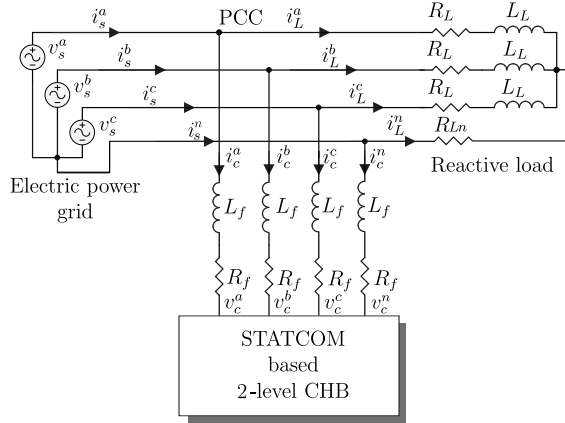


Figura 5.2 Two-level H-bridge APF connection

where n_c is the number of cells, R_{dc} is a resistor connected in parallel to the capacitor C_{dc} that concentrates the overall losses in the DC side, $S_{f_{ij}}$ is the commutation function and the resistor R_f is the parasitic (series) resistance of the inductor L_f .

Predictive control strategy

For two-level H-bridge APFs, the differential equation that models the AC side is [8], [9]:

$$\frac{di_c^{abcn}}{dt} = \frac{v_s^{abcn}}{L_f} - \frac{v_c^{abcn}}{L_f} - \frac{R_f i_c^{abcn}}{L_f} \quad (5.3)$$

the predictive model can be obtained by using a forward Euler discretization method from the continuous time-domain model represented by (5.3), which yields to the following equation:

$$i_c^{abcn}(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abcn}(k) + \frac{T_s}{L_f} \{v_s^{abcn}(k) - v_c^{abcn}(k)\} \quad (5.4)$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^{abcn}(k+1)$ are a prediction of the APF phase currents made at sample k . **Figura 5.3** shows the proposed scheme of the predictive current control technique applied to the three-phase

four-wire two-level H-bridge APF system. In the proposed control the predicted errors are computed for each possible voltage vector as:

$$ei_c^{abcn}(k+1) = i_c^{abcn*}(k+1) - i_c^{abcn}(k+1) \quad (5.5)$$

being ei_c the APF current errors in the AC side, respectively. For each of them a cost function is evaluated. The cost function has been typically defined as a quadratic measure of the predicted error, which can be defined as [10]:

$$J(k+1) = \| ei_c^{abcn}(k+1) \|^2 \quad (5.6)$$

Reference generation

The instantaneous active and reactive power references are obtained from the Clarke transformation approach in $\alpha-\beta-0$ reference frame by using the following transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (5.7)$$

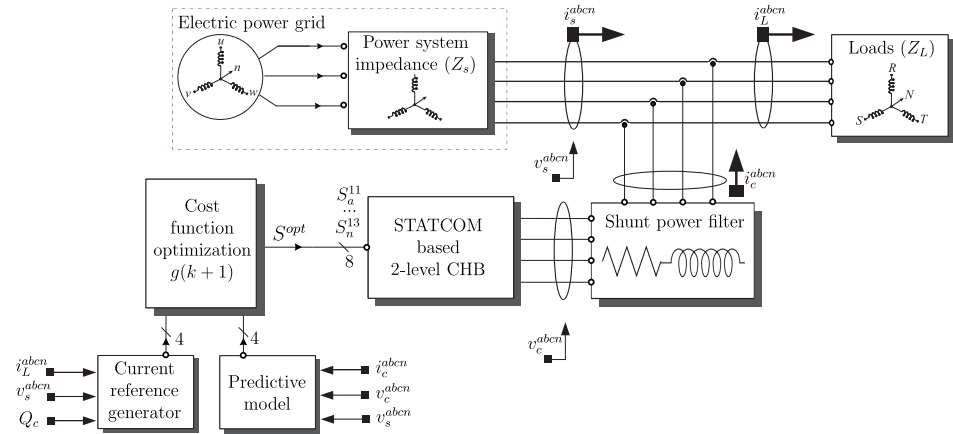


Figure 5.3 Block diagram of the proposed control scheme

Algorithm Optimization algorithm

-
1. Initialize $J_o^a := \infty, J_o^b := \infty, J_o^c := \infty, J_o^n := \infty, \eta := 0$
 2. Compute the STATCOM reference currents. Eqn. (5.13)
 3. **while** $\eta \leq \varepsilon$ **do**
 4. $S_{f_{ij}} \leftarrow S_{f_{ij}}^\eta \quad \forall i = 1, 2, 3, 4 \text{ \& } j = 1, 2, 3, 4$
 5. Compute the STATCOM prediction currents. Eqn. (5.4)
 6. Compute the errors. Eqn. (5.5)
 7. Compute the cost function. Eqn. (5.6)
 8. **if** $J^a < J_o^a$ **then**
 9. $J_o^a \leftarrow J^a, S_a^{opt} \leftarrow S_{a_{ij}}$
 10. **end if**
 11. **if** $J^b < J_o^b$ **then**
 12. $J_o^b \leftarrow J^b, S_b^{opt} \leftarrow S_{b_{ij}}$
 13. **end if**
 14. **if** $J^c < J_o^c$ **then**
 15. $J_o^c \leftarrow J^c, S_c^{opt} \leftarrow S_{c_{ij}}$
 16. **end if**
 17. **if** $J^n < J_o^n$ **then**
 18. $J_o^n \leftarrow J^n, S_n^{opt} \leftarrow S_{n_{ij}}$
 19. **end if**
 20. $\eta := \eta + 1$
 21. **end while**
-

Applying (5.7), the $\alpha - \beta - 0$ current references in the AC side of the APF are obtained from [10]:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (5.8)$$

and i_{c0}^* simplified is:

$$i_{c0}^* = i_{L0} \quad (5.9)$$

where the superscript (*) denotes the reference variables and P_c^*, Q_c^* are the instantaneous active and reactive power references and the P_{c0}^* is the zero sequence instantaneous power, respectively. In order to allow an unitary power factor at the grid side and considering which ideally the APF do not absorb any active power, the instantaneous power references can be written as [11]:

$$P_c^* = 0 \quad (5.10)$$

Tabla 5.2 Parameters description

PARAMETER	Two-Level CHB STATCOM		
	SYMBOL	VALUE	UNIT
Electric frequency of the grid	f_e	50	Hz
Voltage of the electric grid	v_s	310,2	V
Filter resistance	R_f	0,09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	342	V
Load parameters			
Load resistance	R_L	23,2	Ω
Neutral load resistance	R_{Ln}	1	Ω
Change load	R_L	40	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	25	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAR
Zero sequence instantaneous power	P_{c0}^*	$-P_{L0}$	W

$$Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha} \quad (5.11)$$

$$P_{c0}^* = -P_{L0} = -i_{L0} v_{s0} \quad (5.12)$$

being Q_L the instantaneous reactive and P_{L0} is the zero sequence instantaneous power, in the load power to be compensate by the two-level H-bridge APF system. The STATCOM phase currents references used in the optimization process are:

$$i_c^{abc*} = \mathbf{T}^{-1} [i_{c\alpha}^* \ i_{c\beta}^* \ i_{c0}^*]' \quad (5.13)$$

where the superscript (') indicates the transposed matrix.

Simulation results

The proposed control strategy was simulated using MatLab/Simulink considering 40 kHz of sampling frequency and 342 V of the DC side [12]. The electrical parameters as well as the MPC parameters are shown in Table 6.2. Numerical integration using variable step method has been applied to compute the evolution of the time-domain.

Figura 5.4 (upper) shows the active and reactive power on the grid side. The active power remains constant load balanced, when the unbalance occurs to 0.04 s, oscillates due to impedance variations and current circulating in the load. While the reactive power is maintained in the near average zero before and after the load unbalance. In **Figura 5.4** (bottom) i_c^a , i_L^a and i_s^a currents are observed, respectively.

On the hand **Figura 5.5** system behavior in balanced load is observed during the first 0.04 s. At that moment the load is changed in the phase “a”, which makes the load is unbalanced. The dynamics of the system tracks the reference current i_c^{a*} , even if the load imbalance occurs, the system has performed well by injecting reactive power.

Then, in **Figura 5.6** the current in phase “a” of the APF, i_c^a and i_c^{a*} to unbalance load occur, as current monitoring occurs. Moreover, **Figura 5.7** system dynamics is observed in the neutral charge i_L^n , as the injected current i_c^n and reference i_c^{n*} STATCOM. Even at 0.04 s. the system has load balancing and load current i_L^n is zero, the neutral current injected by the APF. When the load unbalance occurs, the current injected by the APF and the neutral current of the load 180 degrees so that compensate. It can observed that the neutral current of the i_s^n source it is on average approximately zero, which meets the parameters of calculation and design of active filter.

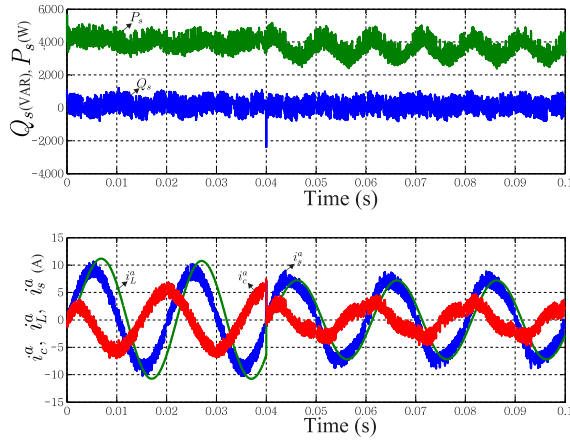


Figura 5.4 Two-level H-bridge APF transient response, active and reactive power compensation

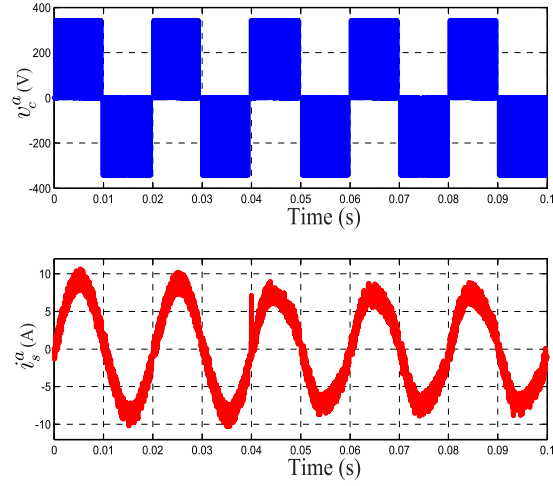


Figure 5.5 Dynamic response evolution of v_c^a , i_s^a and current tracking considering a reactive power step with a load change in the phase “a”

Conclusion

In this paper, a predictive current control technique for a two-level H-bridge APF has been proposed and analyzed. It has been shown that it is possible to compensate the reactive power and instantaneous neutral current in unbalanced load for improving the power factor of the mains. The simulation results confirm the ability of the proposed technique in the field of instantaneous reactive power compensation and neutral current for unbalanced load.

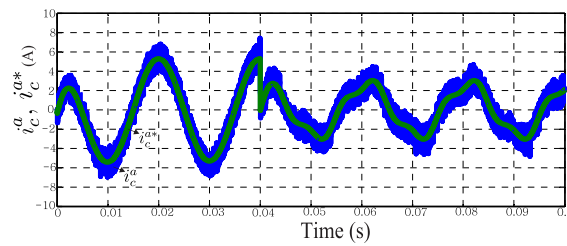


Figure 5.6 Dynamic response evolution of i_c^a , i_c^{a*} and current tracking considering a reactive power step with a load change in the phase “a”

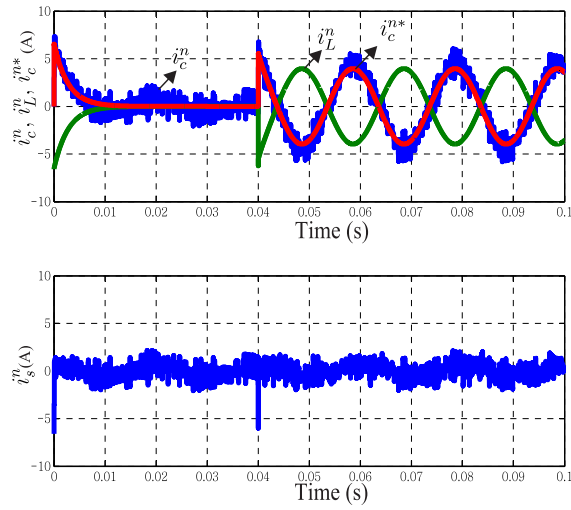


Figura 5.7 Dynamic response evolution of i_c^n , i_c^{n*} and i_L^n neutral current in the load and injection current compensating filter neutral load with a load change in the phase “a”

Acknowledgment

The authors would like to acknowledge the financial support of FONDECYT Regular 1160690 project and Paraguayan Government support provided by means of a CONACYT project 14-INV-096.

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CAPÍTULO 6

ARTICULO 2: MODULATED MODEL PREDICTIVE CURRENT CONTROL FOR H-BRIDGE TWO-LEVEL SINGLE PHASE ACTIVE POWER FILTERS STATCOM

Abstract

Model predictive control techniques are characterized by a variable switching frequency which cause noise as well as large voltage and current ripple. In this paper a predictive control strategy with a fixed switching frequency for a single-phase active power filter, namely modulated model predictive control, is proposed. This technique produces modulated waveform at the output of the converter. The feasibility of this strategy is evaluated using simulation results to demonstrate the advantages of predictive control, such as fast dynamic response and the easy inclusion of nonlinearities. The constraints of the system are maintained but the performance of the system in terms of power quality is improved compared to the traditional model predictive control strategy.

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Introduction

Recently, the use of electronic-based power loads increased greatly and consequently the contamination of the distribution systems. To solve the various problems of power quality in distribution systems, active power filters (APF) and multilevel static synchronous compensators (M-STATCOM) are considered as the best and the most popular solution [1]. The purpose of using a single phase APF is to perform the suppression of harmonic current, reactive power compensation and power factor correction [2], [3]. This can be achieved by the injection of currents at the point of common coupling (PCC) [4]. This type of APF usually requires one H-bridge voltage source inverters (VSI) [5].

Model predictive control (MPC) technique applied to the APF can compensate downtime or nonlinearities in the system. Moreover, MPC provides a flexible control method which is easily extensible for different applications thanks to the advances of the switching devices [6],[7]. However, one of the main disadvantage of this method is its variable switching frequency nature. For instance, the MPC can choose only from a limited number of valid switching states because of the absence of a modulator. This generates noise as well as large voltage and current ripples. The variable switching frequency produces a spread spectrum, decreasing the performance of the system in terms of power quality [8], [9].

Different solutions have been proposed in the literature [10], [11] which allow the operation at fixed switching frequency. The proposed method emulates the implementation of the space vector modulation (SVM). As a consequence, the proposed predictive fixed switching frequency (PfSF) technique uses a switching pattern given through modulation scheme which minimizes the cost function using two active and the zero vectors. The simulation results were analyzed to verify the effectiveness of the proposed method.

This paper is organized as follows: Section II describes the single-phase cascade H-bridge (CHB) APF topology. Section III discusses the proposed modulated control technique model-based predictive control strategy. Section IV discusses the effectiveness of the proposed method considering the simulation results. Finally, concluding remarks are summarized in Section V.

Single-phase CHB STATCOM topology

Figura 6.1 shows the proposed single-phase two-level CHB converter-based STATCOM topology, consisting in one cascade H-bridge cell. The different H-bridge cells have an independent dc-link (C_{dc}). The cell contain four switching devices. Consequently, four switching signals ($S_{f_{ij}}$) are needed in order to control the cell, where f represents the phase (a), i the cell number in the corresponding phase (1) and j the switching device

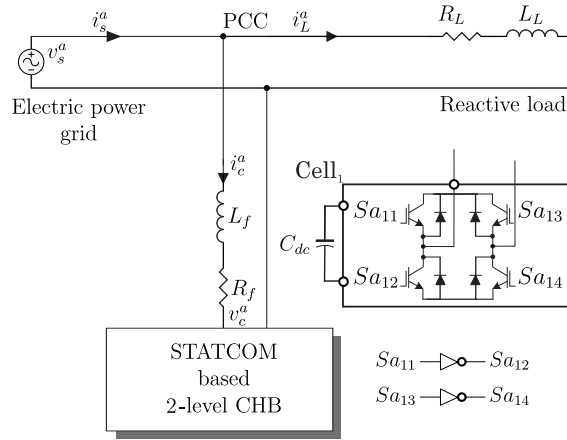


Figure 6.1 Single-phase two-level CHB converter-based STATCOM system and connection

corresponding to the cell (1), respectively. **Table 6.1** shows the allowed combinations of activation signals and the respective output voltages corresponding to the Cell_1 of the phase “a”, where C_{dc} is the voltage of the capacitor. Other possible combinations are not permitted because they cause a short circuit in the dc-link of the cell, to avoid this, only two activation signals S_{a11} and S_{a13} for the particular case of Cell_1 .

CHB Converter-based STATCOM model

The dynamic model of the circuit configuration (**Figure 6.1**) can be obtained by using Kirchhoff’s circuit laws. For modeling purposes, it is assumed that the single-phase voltage sources are balanced and the module has the same capacitance and voltage in their dc side. The CHB converter-based STATCOM is connected at the point of common coupling

Table 6.1 Allowed combinations of activation signals

S_{a11}	S_{a13}	S_{a12}	S_{a14}	v_c^a
1	0	0	1	$+V_{dc}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-V_{dc}$

(PCC). Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equations are obtained:

$$\frac{di_c^a}{dt} = \frac{v_s^a}{L_f} - \frac{R_f}{L_f} i_c^a - \frac{n_c S_{f_{ij}} v_{dc}^a}{L_f} \quad (6.1)$$

$$\frac{dv_{dc}^a}{dt} = \frac{S_{f_{ij}} i_c^a}{C_{dc}} - \frac{v_{dc}^a}{R_{dc} C_{dc}} \quad (6.2)$$

where n_c is the number of cells, R_{dc} is a resistor connected in parallel to the capacitor C_{dc} that concentrates the overall losses in the dc side, $S_{f_{ij}}$ is the commutation function and the resistor R_f is the parasitic (series) resistance of the inductor L_f .

Classic Predictive Model Control

For two level STATCOMs single phase, the differential equation that models the AC side is [9]:

$$\frac{di_c^a}{dt} = \frac{v_s^a}{L_f} - \frac{v_c^a}{L_f} - \frac{R_f i_c^a}{L_f} \quad (6.3)$$

the predictive model can be obtained by using a forward-Euler discretization method from the continuous time-domain model represented by (6.3), which provides the following equation:

$$i_c^a(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^a(k) + \frac{T_s}{L_f} \{v_s^a(k) - v_c^a(k)\} \quad (6.4)$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^a(k+1)$ is a prediction of the STATCOM phase currents made at sample k . **Figura 6.3** shows the proposed scheme applied to the single-phase 2-level CHB converter-based STATCOM system. In the proposed predictive control technique the predicted errors are computed for each possible voltage vector as:

$$ei_c^a(k+1) = i_c^{a*}(k+1) - i_c^a(k+1) \quad (6.5)$$

being ei_c the APF current errors in the AC side, respectively. For each of them a cost function is evaluated. The cost function has been typically defined as a quadratic measure of the predicted error, which can be defined as [7], [8]:

$$g(k+1) = \| ei_c^a(k+1) \|^2 \quad (6.6)$$

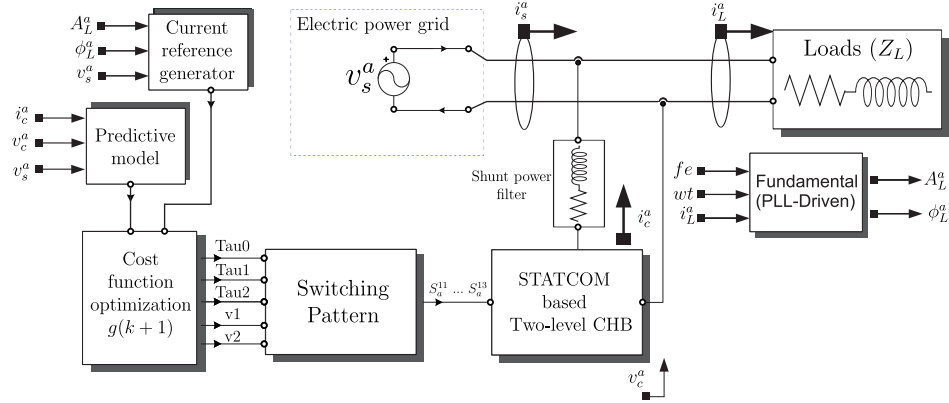


Figure 6.2 Block diagram of the proposed control scheme

Optimization Process

The optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (5.5). Algorithm 1 summarizes the optimization process.

Reference Generation

In the **Figure 6.3** the triangle generator power with respect to the load is shown and explained as follows in points a , b and c :

Algorithm Optimization algorithm

1. Initialize $g_o^a := \infty, \eta := 0$
 2. Compute the STATCOM reference currents. Eqn. (6.8).
 3. **while** $\eta \leq \varepsilon$ **do**
 4. $S_{f_{ij}} \leftarrow S_{f_{ij}}^\eta \forall i = 1, \& g = 1$
 5. Compute the STATCOM prediction currents. Eqn. (6.4).
 7. Compute the errors. Eqn. (6.5).
 8. Compute the cost function. Eqn. (6.6).
 9. **if** $g^a < g_o^a$ **then**
 10. $g_o^a \leftarrow g^a, S_a^{opt} \leftarrow S_{a_{ij}}$
 11. **end if**
 18. $\eta := \eta + 1$
 19. **end while**
-

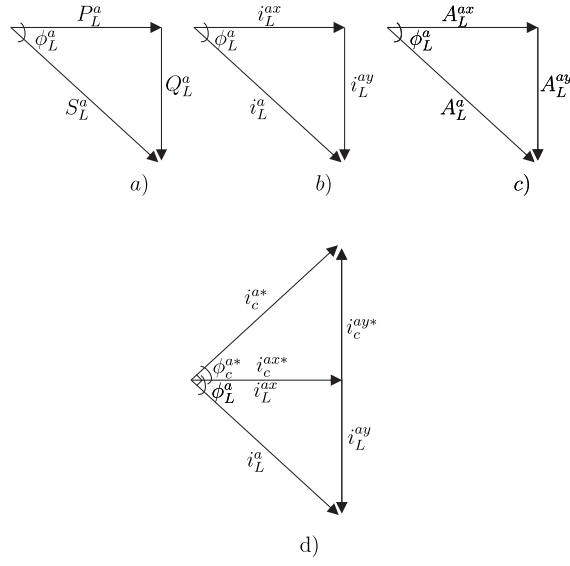


Figura 6.3 Reference generation

a) S , Q , P and ϕ , It represents the apparent power, reactive power, active power and load power factor.

b) i_L^a , i_L^{ay} and i_L^{ax} It represents the module current with their imaginary respective components in the y-axis and x-axis real.

c) A_L^a , A_L^{ay} and A_L^{ax} It represents the modules of the amplitude, imaginary and real components.

d) Through the PLL the amplitude and phase of the measured current are obtained:

$$A_L^{ay} = A_L^a * \sin(\phi_L^a) \quad (6.7)$$

then we apply the reference vector so as to compensate the reactive component of the measured current and therefore reactive power, as shown in **Figura 6.3**:

$$i_L^{ay*} = A_L^{ay} * \sin(\omega t - \pi/2) \quad (6.8)$$

Proposed Modulated control technique

In space vector modulation (SVM) it is possible to define each available vector for the CHB in the plane, as shown in **Figura 6.4**. It is possible to define two sectors which are given by two adjacent vectors, being the first sector, the one between vector v_1 and vector

v_2 which corresponds to the voltage generated by switching state number 1 and switching state number 2, respectively, based on Eqn. (6.2) and Table I. The proposed method is shown in each available vector for the CHB in the plane as shown in **Figura 6.4**. It is possible to define two vectors v_1 and v_2 , with the same idea as the classical predictive control method as it uses the same prediction of the load current indicated in Eqn. (6.4).

Moreover the proposed technique evaluates the prediction of the two active vectors that conform each sector at every sampling time and evaluate the cost function separately for each prediction. The cost function g is evaluated for each case and is the same as the one considered for the classical predictive method. For example, for sector I, the first prediction and cost function g_1 is evaluated for vector v_1 and the second prediction and cost function g_2 is evaluated for vector v_2 . Each prediction is evaluated based on Eqn. (5.4) and the only change is in respect to the calculation of the load voltage v_L^a . The duty cycles for the two active vectors are calculated by solving:

$$\begin{aligned}\tau_1 &= \frac{K}{g_1} \\ \tau_2 &= \frac{K}{g_2}\end{aligned}\tag{6.9}$$

$$\tau_1 + \tau_2 = T_s\tag{6.10}$$

by solving the system of eqn. (5.8), is possible to obtain the expression for K and the expressions for the duty cycles for each vector are given as:

$$\begin{aligned}\tau_1 &= \frac{g_2}{g_1 + g_2} \\ \tau_2 &= \frac{g_1}{g_1 + g_2}\end{aligned}\tag{6.11}$$

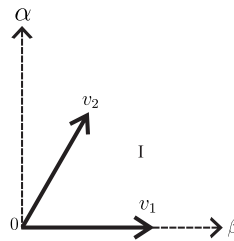


Figura 6.4 Available vectors for the CHB

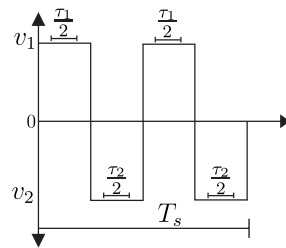
Tabla 6.2 Parameters description

PARAMETER	Two-Level CHB STATCOM		
	SYMBOL	VALUE	UNIT
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Filter inductance	L_f	3	mH
dc-link voltage	v_{dc}	342	V
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	25	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAr

with these expressions, the new cost function, which is evaluated at every sampling time, is defined as

$$g(k+1) = \tau_1 * g_1 + \tau_2 * g_2 \quad (6.12)$$

the two vectors that minimize this cost function are selected and applied to the CHB at the next sampling time. After obtaining the duty cycles and selecting the optimal two vectors to be applied, a switching pattern procedure, such as the one shown in **Figura 6.5**, is adopted with the goal of applying the two active vectors and two zero vectors [12].

**Figura 6.5** Switching pattern

Simulation results

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed modulated control technique applied to the single-phase two-level CHB converter-based STATCOM system, considering the electrical parameters shown in Table 6.2. Numerical integration using Ode45 Dormand-Prince method has been applied to compute the evolution of the variables step by step in the time domain with a relative tolerance of $1e-6$. The performance of the proposed method is compared with the results obtained by a conventional predictive variable control technique in both cases considering a 40 kHz of sampling frequency, setting 342 V of the dc side.

Figura 6.6 shows a transient response when the two-level CHB STATCOM is connected in $t = 0.02$ s, as it is shown in active and reactive power in the load, (bottom) as it is shown in active and reactive power in the power grid. On the other hand, in **Figura 6.7** it can be observed from the simulation results that the phase of grid current (i_c^a) represented in blue with the current reference (i_c^{a*}) of the active filter, suddenly changes to compensate the reactive power showing a fast dynamic response during the transient.

Figura 6.8 shows a comparison analysis from each controller considering the THD of the grid current. A better performance is obtained using the proposed PfSF method mainly in terms of lower total harmonic distortion, due to the fixed switching frequency associated with the modulation process, producing a well-defined discrete current and

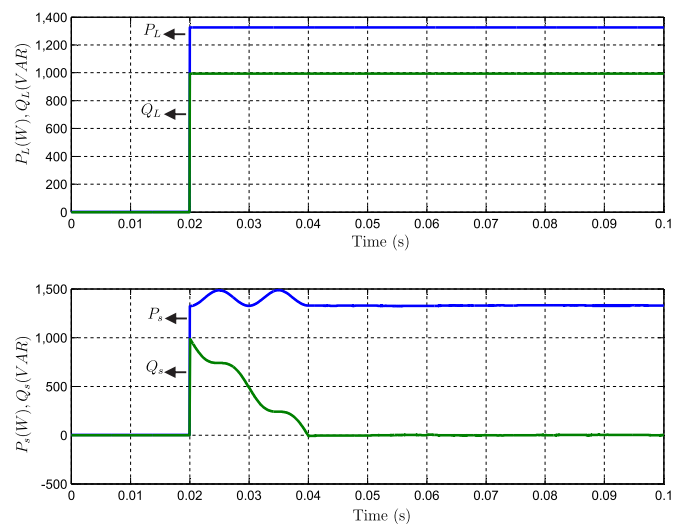


Figura 6.6 Two-level H-bridge APF transient response, active and reactive power compensation (upper) in the load and (bottom) in the power grid

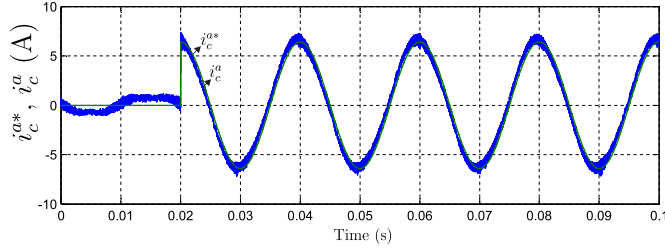


Figura 6.7 Dynamic response evolution of i_c^a , i_c^a and current tracking

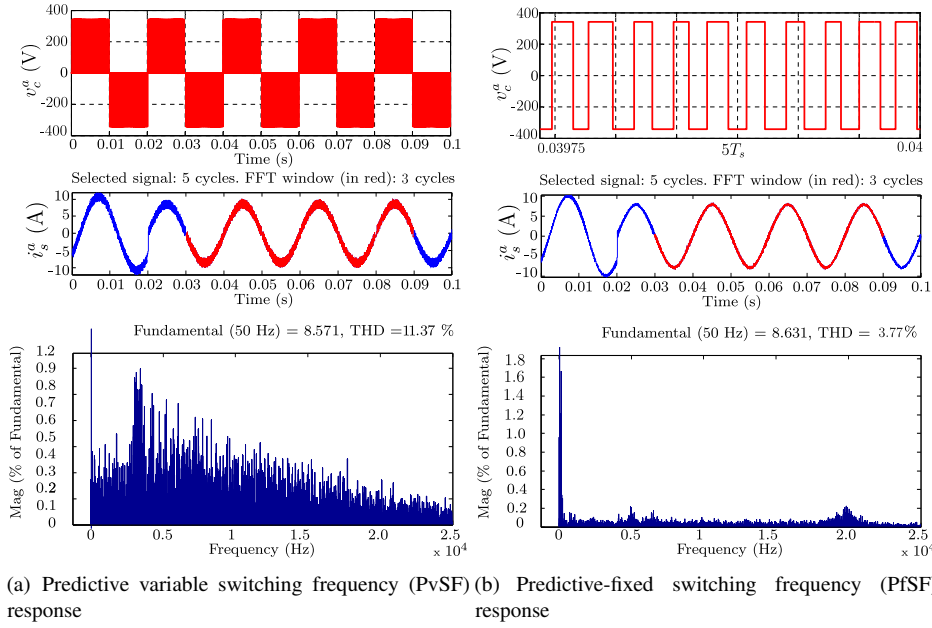


Figura 6.8 Comparison from each controller considering: (upper) the grid current evolution at PCC point, (bottom) the THD of the grid current

voltage spectra in contrast to the PvSF method. The improvement obtained in the THD performance parameter is about 8 % (a drop from 11.37 % to 3.77 %) using the PfSF method, considering the interval where the reactive power is compensated (after 0.02 s).

Conclusion

In this paper, a predictive current control technique with a modulation stage is applied to a single phase two levels CHB STATCOM converter with a fixed switching frequency

while maintaining the advantages of the classical model predictive control techniques such as fast dynamic response and easy inclusion of nonlinearities. Simulation results confirm the capability of the proposed predictive-fixed switching frequency control technique in the field of instantaneous reactive power compensation.

Acknowledgment

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CAPÍTULO 7

ARTICULO 3: MODULATED MODEL PREDICTIVE CURRENT CONTROL FOR H-BRIDGE TWO-LEVEL THREE PHASE ACTIVE POWER FILTERS STATCOM

Abstract

This paper proposes a modulated predictive control strategy for a three-phase two levels H-bridge converter active power filter, namely modulated model predictive current control. Simulation results are shown on the MatLab/Simulink platform to evaluate the feasibility of the proposed strategy, comparing it with the classical predictive control method, such as fast dynamic response and easy inclusion of nonlinearities. The performance of the system improves in terms of energy quality compared to the traditional method of predictive control.

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Introducción

Nowadays, renewable energy sources are of vital importance to satisfy the energy consumption in the future. The three-phase H-bridge AC/DC converter is a popular option for integration of renewable energy sources. The fast development of renewable energy systems also leads to more stringent requirements of AC/DC converters, and more advanced control strategies that can deliver better system reliability and power quality [1]-[3]. The cascade H-bridge (CHB) topology has advantages over the other two topologies because:

- 1) it does not require a very large number of clamping diodes or ying capacitors;
- 2) the power losses are small because the switching frequency of their semiconductor devices are low;
- 3) layout and packaging of the modularized circuit are very easy. Due to these advantages, CHB STATCOM is seen as the best topology in the new generation of reactive power compensation devices and has experienced a fast development in recent years [4]-[6].

The model-based predictive control (MPC) in power electronics refers to the method of predicting the control variable behavior of a discrete-type power converter and then finding the output switching state that minimizes cost function [7]-[9]. The dynamic performance of the control variables is improved because the MPC selects the optimal output switching state that ensures almost zero error between the reference and the predicted value at every sampling period [10]-[12].

This paper presents a model predictive control technique applied to the APF which can compensate downtime or nonlinearities in the system. Moreover, MPC provides a flexible control method which is easily extensible for different applications thanks to the advances of the switching devices [13]-[16]. However, one of the main disadvantages of this method is its variable switching frequency nature. For instance, the MPC can choose only from a limited number of valid switching states because of the absence of a modulator. This generates noise as well as large voltage and current ripples. The variable switching frequency produces a spread spectrum, decreasing the performance of the system in terms of power quality [17]-[20].

The method proposed emulates the implementation of the space vector modulation (SVM) [21]-[24], the proposed predictive fixed switching frequency technique uses a switching pattern given through modulation scheme which minimizes the cost function using two active. The simulation results were analyzed to verify the effectiveness of the method proposed.

This paper is organized as follows: Section II describes the three-phase H-bridge APF topology. Section III discusses the proposed modulated model-based predictive

current control technique. Section IV discusses the effectiveness of the proposed method considering the simulation results. Finally, concluding remarks are summarized in Section V.

Three-phase CHB STATCOM topology

The proposed three-phase two-level CHB converter-based STATCOM topology, shows **Figure 7.1** and consisting in one cascade H-bridge cell. The different H-bridge cells have an independent DC-link (C_{DC}). The cell contains four switching devices. Consequently, four switching signals (S_{fij}) are needed in order to control the cell, where f represents the phase (a), i the cell number in the corresponding phase (1) and j the switching device corresponding to the cell (1), respectively. The allowed combinations of activation signals and the respective output voltages shows in **Table 7.1** and corresponding to the Cell₁ of the phase “a”, where C_{DC} is the voltage of the capacitor. Similar allowed combinations are defined for the other cells. Other possible combinations are not permitted because they cause a short circuit in the DC-link of the cell. To avoid this, only two activation signals and there complementary levels are used as shown in **Figure 7.1** for the particular case of Cell₁.

CHB Converter-based STATCOM model

The dynamic model of the circuit configuration (**Figure 7.1**) can be

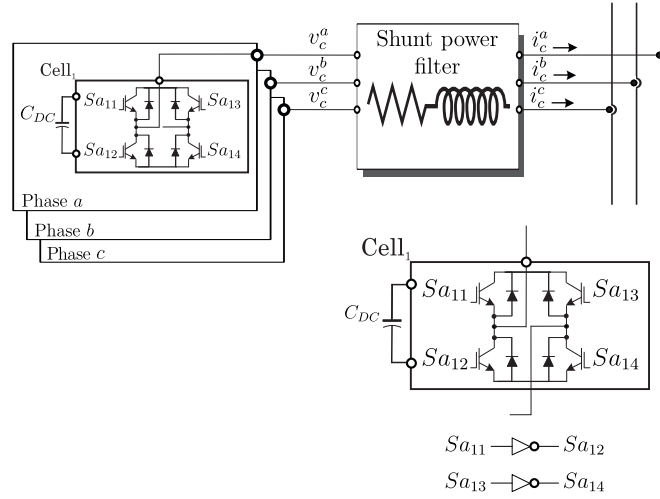


Figure 7.1 Three-phase two-level CHB converter-based STATCOM system and connection

Tabla 7.1 Allowed combinations of activation signals

sa_{11}	sa_{13}	sa_{12}	sa_{14}	v_c^a
1	0	0	1	$+V_{DC}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-V_{DC}$

The dynamic model of the circuit configuration (**Figura 7.1**) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the three-phase voltage sources are balanced and the module has the same capacitance and voltage in their DC side. The CHB converter-based STATCOM is connected at the point of common coupling (PCC). Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equations are obtained:

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{R_f}{L_f} i_c^{abc} - \frac{n_c S_{f_{ij}} v_{DC}^{abc}}{L_f} \quad (7.1)$$

$$\frac{dv_{DC}^{abc}}{dt} = \frac{S_{f_{ij}} i_c^{abc}}{C_{DC}} - \frac{v_{DC}^{abc}}{R_{DC} C_{DC}} \quad (7.2)$$

where n_c is the number of cells, R_{DC} is a resistor connected in parallel to the capacitor C_{DC} that concentrates the overall losses in the DC side, $S_{f_{ij}}$ is the commutation function and the resistor R_f is the parasitic (series) resistance of the inductor L_f .

Classic Predictive Model Control

For three phase two level STATCOMs, the differential equation that models the AC side is [36]:

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{v_c^{abc}}{L_f} - \frac{R_f i_c^{abc}}{L_f} \quad (7.3)$$

The predictive model can be obtained by using a forward-Euler discretization method from the continuous time-domain model represented by (5.3), which provides the following equation:

$$i_c^{abc}(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}(k) + \frac{T_s}{L_f} \{v_s^{abc}(k) - v_c^{abc}(k)\} \quad (7.4)$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^a(k+1)$ is a prediction of the STATCOM phase currents made at sample k . **Figura 7.2** shows the proposed scheme applied to the three-phase two-level CHB converter-based STATCOM system. In the proposed predictive control technique the predicted errors are computed for each possible voltage vector as:

$$ei_c(k+1) = i_c^{abc*}(k+1) - i_c^{abc}(k+1) \quad (7.5)$$

being ei_c the APF current errors in the AC side, respectively. For each of them the cost function is evaluated. The cost function has been typically defined as a quadratic measure of the predicted error, which can be defined as [35], [38]:

$$g(k+1) = \| ei_c(k+1) \|^2 \quad (7.6)$$

Optimization Process

The optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (7.6). Algorithm 1 summarizes the optimization process.

Algorithm Optimization algorithm

1. Initialize $g_o^a := \infty, g_o^b := \infty, g_o^c := \infty, \eta := 0$
 2. Compute the STATCOM reference currents. Eqn. (7.11).
 3. **while** $\eta \leq \varepsilon$ **do**
 4. $S_{f_{ij}} \leftarrow S_{f_{ij}}^\eta \quad \forall i \ \& \ j = 1, 2, 3$
 5. Calculate the STATCOM prediction currents. Eqn. (7.4).
 7. Compute the errors. Eqn. (7.5).
 8. Compute the cost function. Eqn. (7.6).
 9. **if** $g^a < g_o^a$ **then**
 10. $g_o^a \leftarrow g^a, S_a^{opt} \leftarrow S_{a_{ij}}$
 11. **end if**
 12. **if** $g^b < g_o^b$ **then**
 13. $J_o^b \leftarrow g^b, S_b^{opt} \leftarrow S_{b_{ij}}$
 14. **end if**
 15. **if** $g^c < g_o^c$ **then**
 16. $g_o^c \leftarrow g^c, S_c^{opt} \leftarrow S_{c_{ij}}$
 17. **end if**
 18. $\eta := \eta + 1$
 19. **end while**
 20. Compute the switching pattern. Eqn. (7.14).
 21. Compute the new function cost. Eqn. (7.15).
-

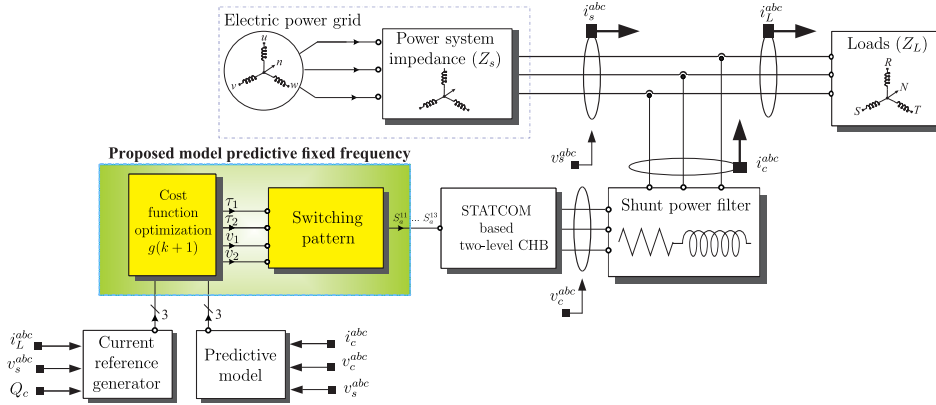


Figure 7.2 Block diagram of the proposed control scheme

Reference Generation

By means of the Clark transformation in the frame of reference $\alpha - \beta$, are obtained the active and reactive power instantaneous power references:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (7.7)$$

Applying (7.12), the $\alpha - \beta$ current references in the AC side of the STATCOM are obtained from:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (7.8)$$

where the superscript (*) denotes the reference variables and P_c^* and Q_c^* are the instantaneous active and reactive power references, respectively. Taking into account that STATCOM does not absorb active power, to allow a unit power factor on the grid side, the instantaneous power references can be written as:

$$P_c^* = 0 \quad (7.9)$$

$$Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha} \quad (7.10)$$

being Q_L the instantaneous reactive load power to be compensate by the H-bridge converter-based STATCOM system. The STATCOM phase currents references used in the optimization process are:

$$i_c^{abc*} = \mathbf{T}^{-1} [i_{c\alpha}^* \ i_{c\beta}^* \ 0]' \quad (7.11)$$

where the superscript (') indicates the transposed matrix.

Modulated control technique proposed

The proposed method uses the two active switching states of CHB $v_1 = +V_{dc}$ and $v_2 = -V_{DC}$, as shown in **Table 7.1**, using same idea as the classical predictive control method as it uses the same prediction of the load current indicated in (7.4), at every sampling time and evaluates the cost function separately for each made prediction. The cost function g is evaluated for each case and is the same as the one considered for the classical predictive method and the duty cycles are calculated by solving:

$$\begin{aligned} \tau_1 &= \frac{K}{g_1} \\ \tau_2 &= \frac{K}{g_2} \end{aligned} \quad (7.12)$$

$$\tau_1 + \tau_2 = T_s \quad (7.13)$$

by solving the system of (7.13), it is possible to obtain the expression for K and the expressions for the duty cycles for each vector, that are given as:

$$\begin{aligned} \tau_1 &= \frac{g_2}{g_1 + g_2} \\ \tau_2 &= \frac{g_1}{g_1 + g_2} \end{aligned} \quad (7.14)$$

with these expressions, the new cost function, which is evaluated at every sampling time, is defined as

$$g(k+1) = \tau_1 g_1 + \tau_2 g_2 \quad (7.15)$$

after obtaining the duty cycles and selecting the optimal cost function to be applied, a switching pattern procedure, such as the one shown in **Figura 7.3**, is adopted with the goal of applying the two cost function [25].

Simulation results

For test of proposed modulation technique applied to the three-phase STATCOM system based on two-level CHB converters, the MatLab/Simulink simulation tool was used, using the parameters shown in **Table 7.2**, applying the numerical integration Ode45 Dormand-Prince for the calculation of step by step variables in the time domain with a relative tolerance of $1e-6$. The performance of the proposed method compares the results obtained with conventional MPC technique with variable switching frequency, in both cases considering a sampling frequency of 40 kHz, setting 342 V of the DC side.

The two-level CHB STATCOM is connected to the $t = 0,04s$, compensating the reactive power in the grid, as shown in **Figura 7.4** the transient response, the upper P_L and Q_L represent the active and reactive power in the load and the bottom P_s and Q_s represent the active and reactive power in the power grid, respectively. On the other hand, **Figura 7.5** shows the transient response of the current injected by the STATCOM i_c^a and the reference current i_c^{a*} .

Finally, we compare the results of the modulation proposal with the classical method using the THD as a harmonic distortion parameter, where the proposed modulation shows a THD improvement of approximately 7 %, a decrease of 9,81 % a 2,77 %, as shown in **Figura 7.6** considering the compensation range of the reactive power (after 0.04 s).

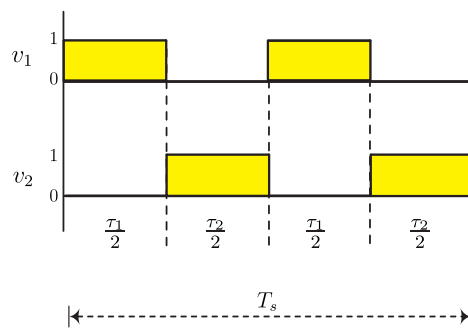
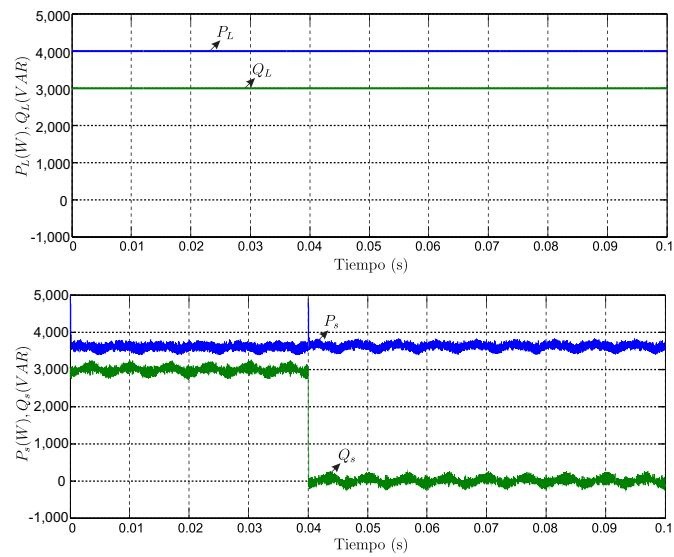


Figura 7.3 Switching pattern

Tabla 7.2 Parameters description

PARAMETER	Two-Level CHB STATCOM		
	SYMBOL	VALUE	UNIT
Electric frequency of the grid	f_e	50	Hz
Voltage of the electric grid	v_s	310.2	V
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{DC}	342	V
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	25	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	Var

**Figura 7.4** Two-level H-bridge APF transient response, active and reactive power compensation (above) in the load and (bottom) in the power grid

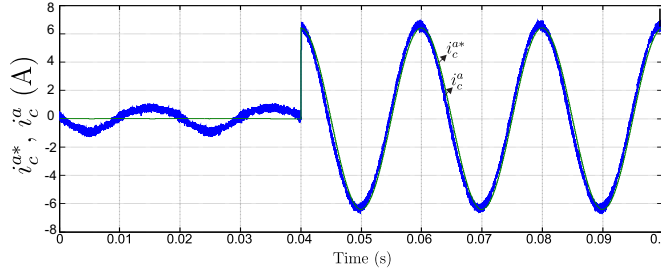


Figura 7.5 Dynamic response evolution of i_c^a , i_c^a and current tracking

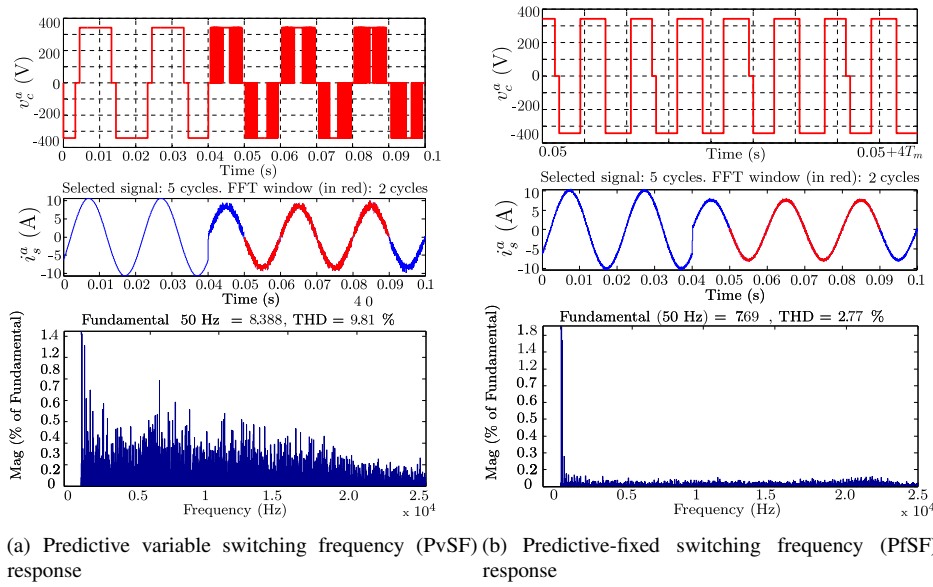


Figura 7.6 Comparison from each controller considering: (above) the grid current evolution at PCC, (bottom) the THD of the grid current

Conclusión

In this work a modulation technique is applied to the control of the predictive current for three-phase two levels CHB STATCOM converter with a fixed switching frequency, maintaining the advantages of classical MPC with fast response, dynamic and easy inclusion of nonlinearities. The results of the simulation confirm the performance of the proposed modulation technique.

Acknowledgment

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APÉNDICE A

OTRAS CONTRIBUCIONES

En este apéndice se realiza una recopilación de los artículos publicados y las actividades de movilidad Erasmus+ realizadas en el marco de esta Tesis de Maestría, en el siguiente orden:

1. Raúl Gregor, **Alfredo Renault**, Leonardo Comparatore, Julio Pacher, Jorge Rodas and Derlis Gregor, “Finite-State Model-Based Predictive Control with Increased Prediction Horizon for a 7-Level Cascade H-Bridge Multilevel STATCOM”, The 20th World Multi-Conference on Systemics, Cybernetics and Informatics (WMSCI 2016), Orlando, FL, Estados Unidos, 05 - 08 Julio 2016.
2. Raúl Gregor, Leonardo Comparatore **Alfredo Renault**, Jorge Rodas, Julio Pacher, Sergio Toledo and Marco Rivera, “A Novel Predictive-fixed Switching Frequency Technique for a Cascade H-bridge Multilevel STATCOM”, 42nd Annual Conference of the IEEE Industrial Electronics Society (IEEE-IECON 2016), Florencia, Italia, 24-27 Octubre 2016. pp. 3672-3677, DOI 10.1109/IECON.2016.7793323.

3. Leonardo Comparatore, **Alfredo Renault**, Julio Pacher, Raúl Gregor, Jorge Rodas, “Model Predictive Current Control with Switcher of Redundant Vectors for a Cascade H-Bridge Multilevel STATCOM”, (ANDESCON), Arequipa, Peru, 2016, pp. 1-4. DOI: 10.1109/ANDESCON.2016.7836229.
4. Leonardo Comparatore, Jorge Rodas, Raúl Gregor, Julio Pacher, **Alfredo Renault** and Marco Rivera, “Model Based Predictive Control for a Three-Phase Cascade H-Bridge Multilevel STATCOM Operating at Fixed Switching Frequency”, Proc. (PEDG 2017), Florianopolis - Brazil, Apr. 17-20, 2017.
5. Julio Pacher, **Alfredo Renault** and Leo Comparatore, “Análisis de la eficiencia de un Puente-H basado en tecnología SiC-MOSFET para aplicaciones de alta frecuencia y media potencia”, Simposio de Ciencia, Tecnologías, Innovación y Educación, Asunción - Paraguay, 25 Octubre 2016.
6. Movilidad realizada en la Universidad de Trento (Italia), a través del programa Erasmus+ del 26/04/2017 al 31/07/2017.

Finite-States Model Predictive Control with Increased Prediction Horizon for a 7-Level Cascade H-Bridge Multilevel STATCOM

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ABSTRACT

This paper presents a finite-states model predictive control technique applied to the three-wire cascade H-bridge multilevel converters for static synchronous compensators. The focus of this paper is to examine the impacts of increasing the prediction horizon on the control performance in terms of reactive power compensation. The proposed approach predicts the future behavior of the control actions considering all possible switching states considering a second step of prediction horizon in order to select the optimal switching vector by using an optimization process considering a defined cost function. The effectiveness of the proposed control approach is analyzed through simulations.

Keywords: Predictive control, cascade H-bridge converter, reactive power compensation.

1. INTRODUCTION

Power quality and efficiency issues have been actually consolidated as a scientific topic in the field of electrical engineering due to the technical requirements for grid connection. In recent years, power factor (PF), voltage collapse, unbalance, excessive harmonics, transients and oscillations, have been a major concern in power transmission and distribution systems. Non-linear loads normally produce disturbances in power transmission and distribution systems, causing a high-level harmonic distortion in phase currents and voltages. Moreover, reactive loads produce a low PF, causing an excessive reactive power (VAR) restricting the maximum active power transfer, adding losses to the power transmission and distribution systems affecting its stability and reliability [1]-[3]. Nowadays, several developments of flexible AC transmission system controllers, such as VAR compensators, have been successfully implemented to overcome the aforementioned drawbacks. In recent years, multilevel converters

have become a popular alternative to overcome the technological restrictions of the actual semiconductor devices that have limited power ratings [4]. Among all multilevel topologies, the cascaded H-bridge (CHB) multilevel converter is often considered as one of the most suitable configuration for high-power static synchronous compensator STATCOM, especially useful for reactive power compensation [5]. CHB converter-based STATCOM systems have been widely used in high-power applications due to its inherent advantages, such as: reduced switching losses, higher conversion efficiency, modular structure, scalability to extended to more levels and higher number of redundant switching states [6]-[8]. Furthermore, in terms of control strategies, the CHB converter topology increases the degrees of freedom due to its modular feature which allows it to impose an asymmetric control approach. In the mentioned control method certain cells could compensate the PF associated with the fundamental frequency and other cells could control the current harmonic distortion [9], [10]. The main contribution of this paper comparing to previous works is focus on providing a background material about the finite-states model predictive control with increased prediction horizon applied to a 7-level cascade H-bridge multilevel STATCOM.

This paper is organized as follows: Section 2 describes the three-wire CHB multilevel STATCOM model. Section 3 discusses the proposed finite-states model predictive control technique with increased prediction horizon. Section 4 discusses the simulation results and provides a comparative analysis with a conventional predictive control technique. Finally, concluding remarks are summarized in Section 5.

2. THREE-PHASE CHB STATCOM MODEL

Fig. 1 (a) shows the proposed three-phase 7-level CHB converter-based STATCOM topology, consisting in three cascade H-bridge cells per phase. The different H-bridge cells have an independent DC-link (C_{dc}). Each cell contains four

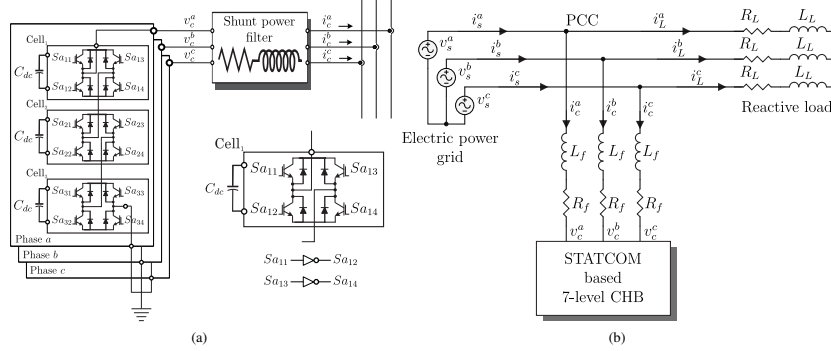


Fig. 1. Propose 7-level CHB converter topology. (a) Three-phase 7-level CHB converter-based STATCOM. (b) CHB converter-based STATCOM connection.

TABLE I
ALLOWED COMBINATIONS OF ACTIVATION SIGNALS

S_{a11}	S_{a13}	S_{a12}	S_{a14}	v_c^a
1	0	0	1	$+C_{dc}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-C_{dc}$

switching devices, resulting in a total of 36 power switches. Consequently, four switching signals (S_{fij}) are needed in order to control each cell, where f represents the phase (a, b and c), i the cell number in the corresponding phase (1, 2 or 3) and j the switching device corresponding to the cell (1, 2, 3 or 4), respectively. Table I shows the allowed combinations of activation signals and the respective output voltages corresponding to the Cell₁ of the phase “a”, where C_{dc} is the voltage of the capacitor. Similar allowed combinations are defined for the other cells. Other possible combinations are not permitted because they cause a short circuit in the DC-link of the cell. To avoid this, only two activation signals and their complementary levels are used as shown in Fig. 1 (a) for the particular case of Cell₁.

A. CHB converter-based STATCOM model

The dynamic model of the circuit configuration shown in Fig. 1 (b) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the three-phase voltage sources are balanced and all modules have the same capacitance and voltage in their DC side. The CHB converter-based STATCOM is connected at the point of common coupling (PCC). Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equations are obtained:

$$\frac{dv_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{R_f}{L_f} i_c^{abc} - \frac{n_c S_{f13} v_{dc}^{abc}}{L_f} \quad (1)$$

$$\frac{dv_{dc}^{abc}}{dt} = \frac{S_{f13} i_c^{abc}}{C_{dc}} - \frac{v_{dc}^{abc}}{R_{dc} C_{dc}} \quad (2)$$

where n_c is the number of cells, R_{dc} is a resistor connected in parallel to the capacitor C_{dc} that concentrates the overall

losses in the DC side and the resistor R_f is the parasitic (series) resistance of the inductor L_f .

B. Finite-state predictive model

For multilevel STATCOMs, the differential equation that models the AC side is [11]:

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{v_c^{abc}}{L_f} - \frac{R_f i_c^{abc}}{L_f} \quad (3)$$

The predictive model can be obtained by using a forward-Euler discretization method from the continuous time-domain model represented by (3), which provides the following equation:

$$i_c^{abc}[k+1] = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}[k] + \frac{T_s}{L_f} \left\{ v_s^{abc}[k] - v_c^{abc}[k] \right\} \quad (4)$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^{abc}[k+1]$ is a prediction of the STATCOM phase currents made at sample k . However, if it is considered that the measured currents and voltages at the beginning of the sampling time, which are used in the control loop, are not valid for the end of sampling time, when the microcontroller sends switching states, due to a microprocessor calculation time delay and also to a fast dynamic response of the system, it is necessary to carry out a second prediction step as follow:

$$i_c^{abc}[k+2] = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}[k+1] + \frac{T_s}{L_f} \left\{ v_s^{abc}[k+2] - v_c^{abc}[k+2] \right\} \quad (5)$$

where $i_c^{abc}[k+1]$ is calculated from (4) using measured STATCOM currents ($i_c^{abc}[k]$) and considering the converter voltages ($v_c^{abc}[k]$) selected by the predictive control in the previous sampling period assuming the $\varepsilon = 2^{2n}$ voltage vectors, where n is the number of H-bridge cells per phase. If $n = 3$, sixty-four possible currents ($i_c^{abc}[k+2]$) are calculated using the possible voltage vectors $v_c^{abc}[k+2]$ per phase, which can be applied in next sampling time.

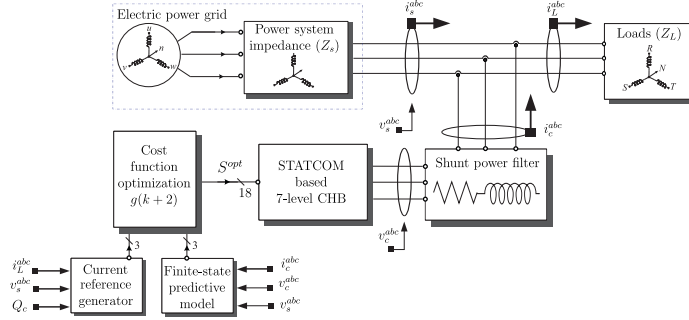


Fig. 2. Block diagram of the proposed control scheme.

3. PROPOSED CONTROL TECHNIQUE

Fig. 2 shows the block diagram of the proposed finite-state model-based predictive control technique applied to the three-phase 7-level CHB converter-based STATCOM system. In the proposed control approach the predicted errors are computed for each possible voltage vector as:

$$ei_c[k+2] = i_c^{abc*}[k+2] - i_c^{abc}[k+2] \quad (6)$$

being $ei_c[k+2]$ the STATCOM current errors in the AC side. The cost function is evaluated sixty-four times by using an optimization process. This cost function provides the ability to define different control criteria incorporating another function objectives. The cost function has been typically defined as a quadratic measure of the predicted error, which can be defined as [12], [13]:

$$g[k+2] = \| ei_c[k+2] \|^2. \quad (7)$$

A. References generation

The instantaneous active and reactive power references are obtained from the Clarke transformation approach in $\alpha - \beta$ reference frame by using the following transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}. \quad (8)$$

Applying (8), the $\alpha - \beta$ current references in the AC side of the STATCOM are obtained from:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (9)$$

where the superscript (*) denotes the reference variables and P_c^* and Q_c^* are the instantaneous active and reactive power references, respectively. In order to allow an unitary power factor at the grid side and considering which ideally the STATCOM do not absorb any active power, the instantaneous power references can be written as:

$$P_c^* = 0 \quad (10)$$

$$Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha} \quad (11)$$

being Q_L the instantaneous reactive load power to be compensate by the H-bridge converter-based STATCOM system. The STATCOM phase currents references used in the optimization process are:

$$i_c^{abc*} = \mathbf{T}^{-1} [i_{c\alpha}^* \ i_{c\beta}^* \ 0]' \quad (12)$$

where the superscript (') indicates the transposed matrix.

B. Optimization process

The optimization is performed by exhaustive search over all possible switching vectors of the control action. Considering the scheme shown in Fig. 1 (a), where the number of H-bridge cells per phase ($f \in \{a, b, c\}$) are three, then each vector S_{fij} consists in $2n$ choice signals, where $j \in \{1, 2, 3\}$. During the optimization process, both the cost function and the predictive model must be computed 64 times at each sampling period to guarantee optimality, since there are 64 possible switching vectors for the case study. These switching vectors represent all possible output voltages of the STATCOM, v_c^a , v_c^b and v_c^c , connected at the PCC point. The output voltages can be represented by the following equation:

$$\begin{bmatrix} v_c^a \\ v_c^b \\ v_c^c \end{bmatrix} = \begin{bmatrix} v_{c1} \\ v_{c2} \\ v_{c3} \end{bmatrix} v_{dc} \quad (13)$$

where v_{c1} , v_{c2} and v_{c3} are the optimal levels of the three-phase 7-level CHB converter-based STATCOM system $(-3, -2, -1, 0, 1, 2, 3)$. The first 15 switching vectors for one phase (a) are shown in Table II.

Finally, the optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (7). Algorithm 1 summarizes the optimization process.

4. SIMULATION RESULTS

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed predictive controller with increased prediction horizon technique applied to the

TABLE II
FIRST 15 SWITCHING VECTORS FOR A THREE-PHASE 7-LEVEL CHB
CONVERTER-BASED STATCOM SYSTEM

$S_{a_{ij}}$						η	v_{c1}
$S_{a_{11}}$	$S_{a_{13}}$	$S_{a_{21}}$	$S_{a_{23}}$	$S_{a_{31}}$	$S_{a_{33}}$		
0	0	0	0	0	0	1	0
0	0	0	0	0	1	2	-1
0	0	0	0	1	0	3	1
0	0	0	0	1	1	4	0
0	0	0	1	0	0	5	-1
0	0	0	1	0	1	6	-2
0	0	0	1	1	0	7	0
0	0	0	1	1	1	8	-1
0	0	1	0	0	0	9	1
0	0	1	0	0	1	10	0
0	0	1	0	1	0	11	2
0	0	1	0	1	1	12	1
0	0	1	1	0	0	13	0
0	0	1	1	0	1	14	-1
0	0	1	1	1	0	15	1
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

Algorithm 1 Optimization algorithm

1. Initialize $J_o^a := \infty, J_o^b := \infty, J_o^c := \infty, \eta := 0$
2. Compute the STATCOM reference currents (Eqn. 12)
3. Compute the first prediction step (Eqn. 4)
4. **while** $\eta \leq \varepsilon$ **do**
5. $S_{f_{ij}} \leftarrow S_{f_{ij}}^\eta \forall i = 1, 2, 3 \ \& \ j = 1, 2, 3$
6. Compute the second prediction step (Eqn. 5)
7. Compute the tracking error (Eqn. 6)
8. Compute the cost function (Eqn. 7)
9. **if** $J^a < J_o^a$ **then**
10. $J_o^a \leftarrow J^a, S_{a_{ij}}^{opt} \leftarrow S_{a_{ij}}$
11. **end if**
12. **if** $J^b < J_o^b$ **then**
13. $J_o^b \leftarrow J^b, S_{b_{ij}}^{opt} \leftarrow S_{b_{ij}}$
14. **end if**
15. **if** $J^c < J_o^c$ **then**
16. $J_o^c \leftarrow J^c, S_{c_{ij}}^{opt} \leftarrow S_{c_{ij}}$
17. **end if**
18. $\eta := \eta + 1$
19. **end while**
20. Apply the optimum vector $S^{opt} \in \{S_{a_{ij}}^{opt}, S_{b_{ij}}^{opt}, S_{c_{ij}}^{opt}\}$

three-phase 7-level CHB converter-based STATCOM system, considering the electrical parameters shown in Table III. Numerical integration using Runge-Kutta method has been applied to compute the evolution of the variables step by step in the time domain. The performance of the proposed finite-states model predictive control method has been analyzed in terms of reactive power compensation as well as harmonic distortion considering a 40 kHz of sampling frequency, setting 114 V in the DC side as it is shown in Fig. 1 (a).

Fig. 3 shows a simulation results performed in order to analyze the feasibility of the proposed control technique under steady-state and transient conditions. Fig. 3 (upper) shows a step in the instantaneous reactive power reference where it is possible to notice the effect of reactive power compensation. Moreover, Fig. 3 (middle), shows the tracking current dynamic performance for a step change of the reactive power reference.

TABLE III
PARAMETERS DESCRIPTION

7-Level CHB STATCOM			
PARAMETER	SYMBOL	VALUE	UNIT
Electric frequency of the grid	f_e	50	Hz
Voltage of the electric grid	v_s	310.2	V
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	114	V
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	25	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAR

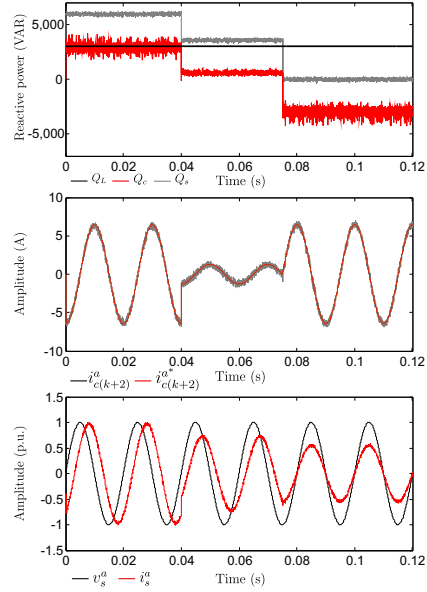


Fig. 3. CHB STATCOM transient response: (upper) reactive power compensation, (middle) tracking current and (bottom) grid voltage and current.

Finally, Fig. 3 (bottom) shows the effect of the grid current when the 7-level CHB STATCOM compensates the reactive power after $t = 0.075$ s. It can be observed from the simulation results that the phase of grid current represented in red color, suddenly changes to compensate the reactive power showing a fast dynamic response during the transient.

Next, in order to compare quantitatively the proposed control method with the conventional predictive control technique the

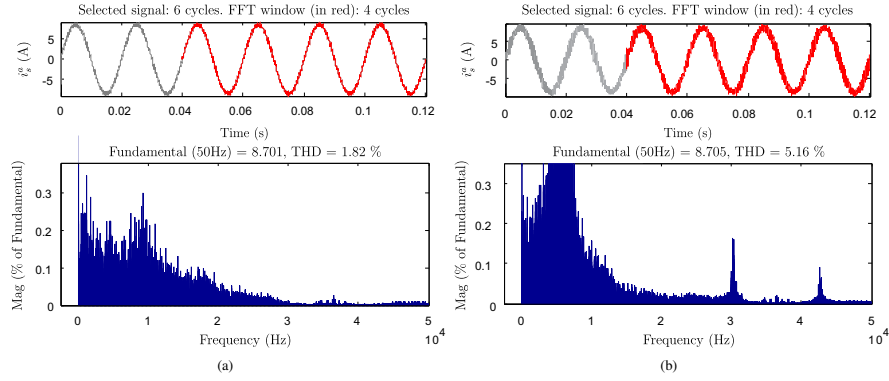


Fig. 4. Comparison performance considering: (upper) the grid current and (bottom) the THD of the grid current. (a) Second prediction step response. (b) First prediction step response.

mean squared error (MSE) and the total harmonic distortion (THD) are used as figures of merit. The equations are represented by (14) and (15), respectively:

$$\text{MSE}(\Psi) = \sqrt{\frac{1}{N} \sum_{j=1}^N \Psi_j^2} \quad (14)$$

$$\text{THD} = \sqrt{\frac{1}{i_1^2} \sum_{i=2}^N i_i^2} \quad (15)$$

where N is the number of vector elements, Ψ_j are the instantaneous predicted errors, i_1 is the amplitude of the fundamental frequency of the analyzed current, and i_i are the current harmonics.

Fig. 4 shows a comparison analysis between the proposed second prediction step controller and the conventional first prediction step controller considering: (upper) the grid current of the phase a and (bottom) the THD of the analyzed grid current. As shown in Fig. 4 (a) a better performance is obtained using the proposed second prediction step controller mainly in terms of lower THD when the delays are considered in the control equations. This characteristic produces a well-defined discrete current spectra in contrast with the conventional one step prediction method. The improvement obtained in the THD performance parameter is about 65% (a drop from 5.16% to 1.82%) using the proposed method, considering the interval where the reactive power is compensated (after 0.05 s).

Furthermore, the second step predictive current control loop is analyzed in more detail to quantify the improvements obtained using the proposed control method in terms of MSE. Fig. 5 shows the dynamic response obtained when a step in the reference reactive power (Q_c) from 3,000 to -3,000 VAR at $t = 0.02$ s is applied. Under these operating conditions the obtained MSE performance parameters are also reduced using the proposed method, from 0.9816 to 0.3224 which represents an improvement of 67%. As observed, from the simulation results, the current reference tracking of the proposed method

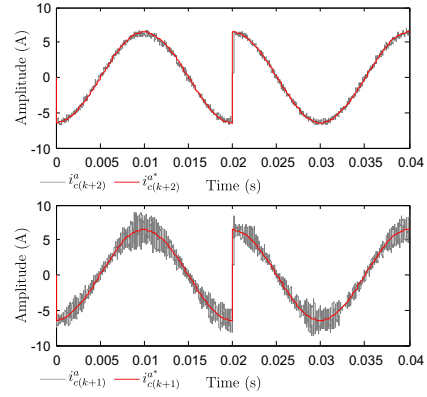


Fig. 5. CHB STATCOM current tracking analysis: (upper) proposed method based on second prediction step and (bottom) conventional method.

is very good, being even able to reduce the harmonic distortion of the currents without affecting the dynamic response during the transient, which is very fast.

5. CONCLUSION

In this paper an enhanced predictive current control technique applied to the three-wire CHB multilevel converters STATCOM has been proposed, analyzed and compared with the conventional one step predictive control approach. The simulation results confirm the capability of the proposed control technique to compensate the instantaneous reactive power and shows that it is possible to increase significantly the performance of the control algorithm when is considered the microprocessor

calculation time delay defining a second step prediction horizon. A comparative simulation results performed with reference to the conventional method show improvements in terms of total harmonic distortion and mean squared error as well.

Acknowledgment

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A Novel Predictive-Fixed Switching Frequency Technique for a Cascade H-Bridge Multilevel STATCOM

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Abstract—There are several control techniques for active power filter applications. This paper presents a new alternative of predictive current control for a cascade H-bridge multilevel converter, where the optimal vector selected by the predictive controller is used for a modulation stage to obtain a fixed switching frequency. Simulation results validate the proposal where almost similar results can be obtained in comparison with the traditional methods.

Index Terms—Active power filters, cascade H-bridge converter, fixed switching frequency, predictive control.

I. INTRODUCTION

In recent years, power quality and efficiency issues have been consolidated as a scientific topic in the field of electrical engineering due to technical requirements for grid connection. Actually, power factor (PF), voltage collapse, unbalance, excessive harmonics, transients and oscillations, have been a major concern in power transmission and distribution systems. Non-linear loads normally produce disturbances in power transmission and distribution systems, causing a high-level harmonic distortion in the phase currents and voltages. Moreover, reactive loads produce a low PF, causing an excessive reactive power (VAR) restricting the maximum active power transfer, adding losses to the power transmission and distribution systems affecting its stability and reliability [1], [2]. Nowadays, several developments of flexible AC transmission system controllers, such as VAR compensators, have successfully been implemented to overcome the aforementioned drawbacks [3], [4]. Recently, multilevel converters have become a popular alternative to overcome the technological restrictions of the actual semiconductor devices that have limited power ratings [5]. Among all multilevel topologies, the cascaded H-bridge (CHB) multilevel converter is often considered as one of the most suitable configuration for high-power static synchronous compensator STATCOM, especially useful for reactive power compensation [6]. CHB converter-based STATCOM systems have been widely used in high-power applications due to its inherent advantages such as: reduced switching losses, higher conversion efficiency, modular structure, scalability to extended to more levels and higher number of redundant switching states [7]–[10]. Furthermore,

in terms of control strategies, the CHB converter topology increases the degrees of freedom due to its modular feature which allows to impose an asymmetric control approach. In the mentioned control method certain cells could compensate the PF associated with the fundamental frequency and other cells could control the current harmonic distortion [11], [12].

This paper proposes a simple and efficient predictive control technique applied to the three-phase 7-level CHB converter-based STATCOM system in combination with a modulation stage. The predictive model is obtained from the dynamic equations of the compensation system. Simulation results are analyzed and compared with the obtained by using the conventional predictive control approach.

This work is organized as follows. Section II describes the three-wire CHB multilevel STATCOM topology. Section III introduces the proposed predictive control technique including the CHB STATCOM duty cycles calculation approach. A comparative analysis of the proposed control technique with a conventional predictive control approach based on variable switching frequency are discussed in Section IV. Finally, the main feature of the proposed predictive-fixed switching frequency technique are summarized in Section V.

II. CHB STATCOM TOPOLOGY

Fig. 1 shows the proposed three-phase 7-level CHB converter-based STATCOM topology, consisting in three cascade H-bridge cells per phase. The different H-bridge cells have an independent DC-link. Each cell contains four switching devices, resulting in a total of 36 power switches. Consequently, four switching signals (S_{fij}) are needed to control each cell, where f represents the phase (a , b and c), i the cell number in the corresponding phase (1, 2 or 3) and j the switching device corresponding to the cell (1, 2, 3 or 4), respectively. Table I shows the allowed combinations of activation signals and the respective output voltages corresponding to the Cell₁ of the phase “a”, where C_{dc} is the voltage of the capacitor. Similar allowed combinations are defined for the other cells. Other possible combinations are not permitted because they cause a short circuit in the DC-link of the cell. To avoid this, only two activation signals and they complementary

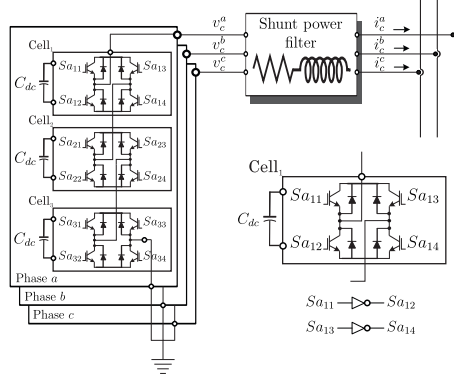


Fig. 1. Three-phase 7-level CHB converter-based STATCOM system.

TABLE I
ALLOWED COMBINATIONS OF ACTIVATION SIGNALS

S_{a11}	S_{a13}	S_{a12}	S_{a14}	v_c^a
1	0	0	1	$+C_{dc}$
1	1	0	0	0
0	0	1	1	0
0	1	1	0	$-C_{dc}$

levels are used as shown in Fig. 1 for the particular case of Cell₁.

A. CHB Converter-based STATCOM model

The dynamic model of the circuit configuration (Fig. 2) can be obtained by using Kirchhoff's circuit laws. For modeling purposes, it is assumed that the three-phase voltage sources are balanced and all modules have the same capacitance and voltage in their DC side. The CHB converter-based STATCOM is connected at the point of common coupling (PCC). Applying Kirchhoff's voltage law for the AC side of the STATCOM, the following equations are obtained:

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{R_f}{L_f} i_c^{abc} - \frac{n_c S_{f_{ij}} v_{dc}^{abc}}{L_f} \quad (1)$$

$$\frac{dv_{dc}^{abc}}{dt} = \frac{S_{f_{ij}} i_c^{abc}}{C_{dc}} - \frac{v_{dc}^{abc}}{R_{dc} C_{dc}} \quad (2)$$

where n_c is the number of cells, R_{dc} is a resistor connected in parallel to the capacitor C_{dc} that concentrates the overall losses in the DC side, $S_{f_{ij}}$ is the commutation function and the resistor R_f is the parasitic (series) resistance of the inductor L_f .

B. Predictive model

For multilevel STATCOMs, the differential equation that models the AC side is [13]:

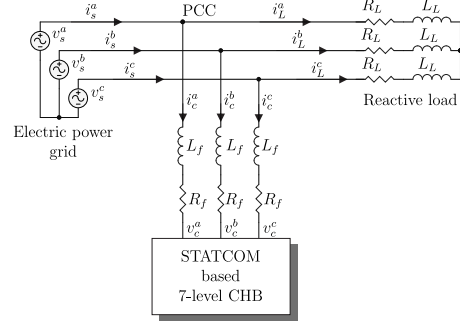


Fig. 2. CHB converter-based STATCOM connection.

$$\frac{di_c^{abc}}{dt} = \frac{v_s^{abc}}{L_f} - \frac{v_c^{abc}}{L_f} - \frac{R_f i_c^{abc}}{L_f} \quad (3)$$

The predictive model can be obtained by using a forward-Euler discretization method from the continuous time-domain model represented by (3), which provides the following equation:

$$i_c^{abc}(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^{abc}(k) + \frac{T_s}{L_f} \{v_s^{abc}(k) - v_c^{abc}(k)\} \quad (4)$$

being T_s the sampling time, k the actual sample and $i_c^{abc}(k+1)$ the prediction of the STATCOM phase currents made at sample k .

Moreover, the dynamics of the DC side, considering the ideal case ($R_{dc} = \infty$) can be model by the following equation:

$$v_{dc}^{abc}(k+1) = v_{dc}^{abc}(k) + \frac{T_s S_{f_{ij}}(k) i_c^{abc}(k)}{C_{dc}} \quad (5)$$

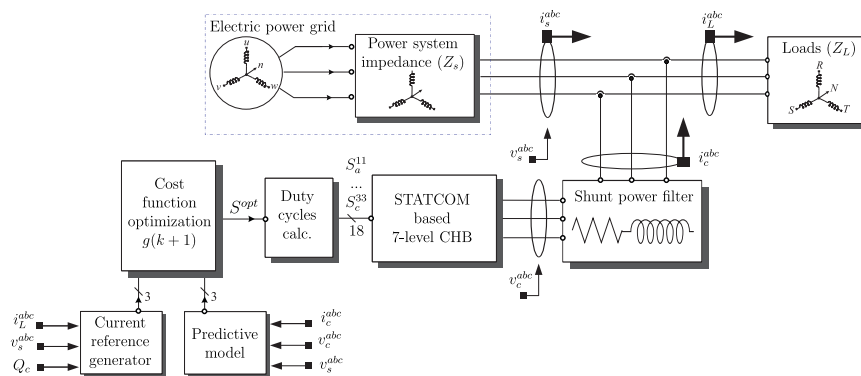
III. PROPOSED CONTROL TECHNIQUE

Fig. 3 shows the proposed scheme applied to the three-phase 7-level CHB converter-based STATCOM system. In the proposed predictive control technique the predicted errors are computed for each possible voltage vector as:

$$ei_c(k+1) = i_c^{abc*}(k+1) - i_c^{abc}(k+1) \quad (6)$$

$$ev_{dc}(k+1) = v_{dc}^{abc*}(k+1) - v_{dc}^{abc}(k+1) \quad (7)$$

being $ei_c(k+1)$ and $ev_{dc}(k+1)$ the STATCOM current errors in the AC side and the capacitor voltage errors in the DC side, respectively. After performing the prediction of (6) and (7), a defined cost function is computed recursively at each sampling period. The cost function provides the ability of incorporating different control objectives. This function has been typically defined as a quadratic measure of the predicted error, which can be defined as [14], [15]:



$$q(k+1) = \|ei_c(k+1)\|^2 + \lambda \|ev_{dc}(k+1)\|^2 \quad (8)$$

being λ the weighting factor that gives priority to the control objectives.

A. Reference generation

The instantaneous active and reactive power references are obtained from the Clarke transformation approach in $\alpha - \beta$ reference frame by using the following transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (9)$$

Applying (9), the $\alpha - \beta$ current references in the AC side of the STATCOM are obtained from:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (10)$$

where the superscript (*) denotes the reference variables and P_c^* and Q_c^* are the instantaneous active and reactive power references, respectively. In order to allow an unitary power factor at the grid side and considering which ideally the STATCOM do not absorb any active power, the instantaneous power references can be written as:

$$P_c^* = 0 \quad (11)$$

$$Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha} \quad (12)$$

being Q_L the instantaneous reactive load power to be compensate by the H-bridge converter-based STATCOM system. The STATCOM phase currents references used in the optimization process are:

$$i_c^{abc*} = \mathbf{T}^{-1} [i_{c\alpha}^* \ i_{c\beta}^* \ 0]' \quad (13)$$

where the superscript (') indicates the transposed matrix.

B. Optimization process

The optimization is performed by exhaustive search over all possible switching vectors of the control action. If n is the number of H-bridge cells per phase (f), then each vector $S_{f,j}$ consists in $2n$ choice signals, where $j = 1, \dots, \phi$; being ϕ the number of phases. Moreover, the number of possible switching vectors per phase can be defined as $\varepsilon = 2^{2n}$. During the optimization process, both, the cost function and the predictive model must be computed 64 times at each sampling period to guarantee optimality, since there are 64 possible switching vectors for the case study. These switching vectors represent all possible output voltages of the STATCOM, v_a^* , v_b^* and v_c^* , connected at the PCC. The output voltages can be represented by the following equation:

$$\begin{bmatrix} v_c^a \\ v_c^b \\ v_c^c \end{bmatrix} = \begin{bmatrix} v_{c1} \\ v_{c2} \\ v_{c3} \end{bmatrix} v_{dc} \quad (14)$$

where v_{c1} , v_{c2} and v_{c3} are the optimal levels of the three-phase 7-level CHB converter-based STATCOM system $(-3, -2, -1, 0, 1, 2, 3)$. The first 15 switching vectors for one phase (a) are shown in Table II.

TABLE II
FIRST 15 SWITCHING VECTORS FOR A THREE-PHASE 7-LEVEL CHB
CONVERTER-BASED STATCOM SYSTEM

$S_{a_{ij}}$						η	v_{c1} value
S_{a11}	S_{a13}	S_{a21}	S_{a23}	S_{a31}	S_{a33}		
0	0	0	0	0	0	1	0
0	0	0	0	0	1	2	-1
0	0	0	0	1	0	3	1
0	0	0	0	1	1	4	0
0	0	0	1	0	0	5	-1
0	0	0	1	0	1	6	-2
0	0	0	1	1	0	7	0
0	0	0	1	1	1	8	-1
0	0	1	0	0	0	9	1
0	0	1	0	0	1	10	0
0	0	1	0	1	0	11	2
0	0	1	0	1	1	12	1
0	0	1	1	0	0	13	0
0	0	1	1	0	1	14	-1
0	0	1	1	1	0	15	1
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

Finally, the optimization algorithm selects the optimum vector S^{opt} that minimizes the defined cost function represented by (8). Algorithm 1 summarizes the optimization process.

Algorithm 1 Optimization algorithm

1. Initialize $J_o^a := \infty, J_o^b := \infty, J_o^c := \infty, \eta := 0$
2. Compute the STATCOM reference currents. Eqn. (13).
3. **while** $\eta \leq \varepsilon$ **do**
4. $S_{f_{ij}} \leftarrow S_{f_{ij}}^\eta \forall i \& j = 1, 2, 3$
5. Calculate the STATCOM prediction currents. Eqn. (4).
6. Compute the dynamics of the DC side. Eqn. (5).
7. Compute the errors. Eqns. (6) & (7).
8. Compute the cost function. Eqn. (8).
9. **if** $J^a < J_o^a$ **then**
10. $J_o^a \leftarrow J^a, S_{a_{ij}}^{opt} \leftarrow S_{a_{ij}}$
11. **end if**
12. **if** $J^b < J_o^b$ **then**
13. $J_o^b \leftarrow J^b, S_{b_{ij}}^{opt} \leftarrow S_{b_{ij}}$
14. **end if**
15. **if** $J^c < J_o^c$ **then**
16. $J_o^c \leftarrow J^c, S_{c_{ij}}^{opt} \leftarrow S_{c_{ij}}$
17. **end if**
18. $\eta := \eta + 1$
19. **end while**
20. Compute the duty cycles. Eqn. (15).

C. CHB STATCOM duty cycles calculation

The CHB STATCOM duty cycles calculation of the proposed algorithm proceeds as follows. For a desired instantaneous active and reactive power references, the control algorithm determine the optimal vector (S_f^{opt}) that minimizes (8). The optimal vector provides the optimum voltages ($v_c^{a,opt}, v_c^{b,opt}, v_c^{c,opt}$) in terms of the CHB STATCOM current and voltage errors, respectively. Instead of applying the selected voltage vector to the CHB STATCOM during the whole

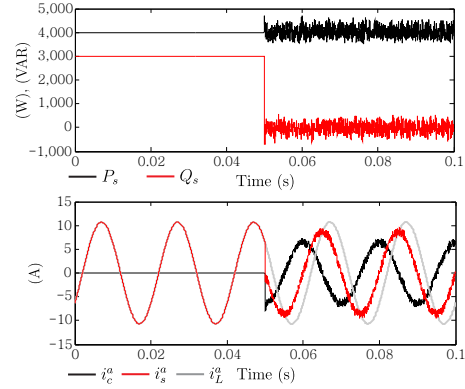


Fig. 4. CHB STATCOM transient response: (upper) reactive power compensation, (bottom) currents evolution.

switching period, which is the standard procedure in conventional predictive control schemes, the proposed algorithm uses S_f^{opt} to calculate the duty cycles by using the following equation:

$$\begin{bmatrix} \tau_a \\ \tau_b \\ \tau_c \end{bmatrix} = \frac{1}{3} (v_{dc}^{-1}) [v_c^{a,opt} \ v_c^{b,opt} \ v_c^{c,opt}]' \quad (15)$$

where τ_f is the duty cycles vector and the subscript $f = a, b, c$ are associated with the CHB STATCOM phase voltages and are normalized between -1 and 1. The calculation of the duty cycles is proposed as an optimization problem aimed to minimize the prediction error. This procedure can be considered as a systematic application in one sampling period of the optimal combination of more than one vector to minimize the CHB STATCOM current errors in the AC side and the capacitor voltage errors in the DC side, respectively.

IV. SIMULATION RESULTS

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed PfSF control technique applied to the three-phase 7-level CHB converter-based STATCOM system, assuming the parameters shown in Table III. Numerical integration based on Runge-Kutta method has been used to calculate the evolution of the variables step by step in the time domain. The performance of the proposed predictive-fixed switching frequency (PfSF) method is compared with the results obtained by a conventional predictive variable switching frequency (PvSF) control technique considering a 15 kHz of sampling frequency and setting 114 V of the DC side.

The cost function defined in (8) with $\lambda = 0.001$ is used to evaluate the dynamic performance of the PfSF and PvSF methods under steady-state and transient conditions.

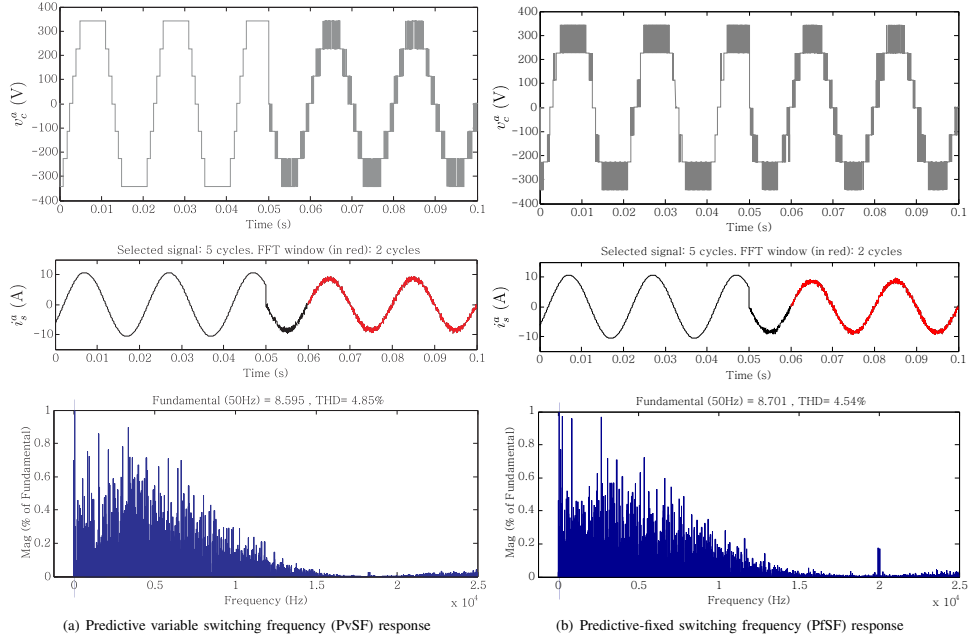


Fig. 5. Comparative analysis considering: (upper) the phase voltage at PCC, (middle) the grid current and (bottom) the THD of the grid current.

TABLE III
PARAMETERS DESCRIPTION

PARAMETER	7-Level CHB STATCOM		
	SYMBOL	VALUE	UNIT
Electric frequency of the grid	f_e	50	Hz
Voltage of the electric grid	v_s	310.2	V
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	114	V
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	66	μs
Active power reference	P_c^*	0	W
Ideal Reactive power reference	Q_c^*	$-Q_L$	VAR

Fig. 4 (bottom) shows a transient response when the 7-level CHB STATCOM is connected in $t = 0.05$ s, as it is shown in Fig. 4 (upper). It can be observed from the simulation results that the phase of grid current (i_g^a) represented in red color, suddenly changes to compensate the reactive power showing a fast dynamic response during the transient. Next, in order

to compare quantitatively both controllers the mean squared error (MSE) and the total harmonic distortion (THD) are used as figures of merit. The equations are represented by (16) and (17), respectively as:

$$MSE(\Psi) = \sqrt{\frac{1}{N} \sum_{j=1}^N \Psi_j^2} \quad (16)$$

$$THD = \sqrt{\frac{1}{i_1^2} \sum_{i=2}^N i_i^2} \quad (17)$$

where N is the number of vector elements, i_1 is the amplitude of the fundamental frequency of the analyzed current, and i_i are the current harmonics.

Fig. 5 shows a comparative analysis of both control systems considering (upper) the phase voltage evolution at PCC, (middle) the grid current and (bottom) the THD of the grid current. Simulation results show a better performance in terms of lower THD using the proposed PfSF method. This feature is associated to the fixed switching frequency produced by modulation process that yield a well-defined discrete current and voltage spectra in contrast to the simulation results obtained by the PvSF method. The THD improvement is quantified

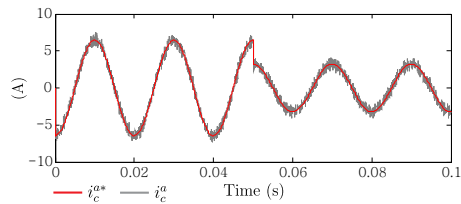


Fig. 6. Dynamic response evolution of i_c^a and current tracking considering a reactive power step.

about 8% (a drop from 4.85% to 4.54%) using the PfSF method, considering the interval where the reactive power is compensated (after 0.05 s).

Furthermore, the predictive current control loop is analyzed in detail in order to quantify the improvements obtained using the proposed control algorithm in terms of MSE. Fig. 6 shows the dynamic response obtained when a step in the reference reactive power (Q_c) from 3,000 to 1,500 VAR at $t = 0.05$ s is applied. Under these operating conditions the proposed PfSF method introduces improvements in terms of lower MSE, from 0.3945 (PvSF) to 0.3771 (PfSF). Moreover as observed from the simulation results, the current reference tracking of the proposed PfSF method is very good, being even able to reduce the THD of the currents without affecting the dynamic response during the transient, which is however very fast.

V. CONCLUSION

In this paper, an alternative predictive current control technique with a modulation stage is applied to a three-wire CHB multilevel STATCOM converter. The theoretical results show that it is possible to combine the use of predictive control with modulation techniques to obtain better performance than a classic predictive control approach. Simulation results confirm that maintaining the modulation technique avoids the variable switching frequency inherent in conventional predictive controllers, easing the switch selection and providing a more adequate harmonic profile. Furthermore, the proposed technique proved to be viable in the field of instantaneous reactive power compensation.

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Model Based Predictive Control with Switcher of Redundant Vectors for a Cascade H-Bridge Multilevel STATCOM

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Abstract—Conventional model based predictive control for cascade H-bridge multilevel STATCOM produces a different switching pattern for different cells. As a consequence, stresses, DC-link imbalance and active power losses are generated among the cells. To solve the aforementioned issues, this paper proposes to include a switcher of redundant vectors on the conventional model based predictive method. Additionally, improve the performance in terms of total harmonic distortion and remain focus the reactive power compensation. Simulation results are analyzed to verify the effectiveness of this proposal.

Index Terms—Active power filters, cascade H-bridge converter, predictive control, switcher of redundant vectors.

I. INTRODUCTION

New generation of power electronic systems, e.g., static synchronous compensators (STATCOMs), which aims to improve the power quality in electrical systems, and its control, is mainly due to the evolution of power semiconductor devices joined to the advancement of digital signal processors (DSPs), with the purposes of control in power converters, their advantages are beginning to be exploited [1]. Low power factor (PF), voltage collapse, unbalance loads, excessive harmonics generated by nonlinear loads, transients and oscillations are the main problems which affect the power quality in distribution systems [2]-[3]. One of the main topologies of STATCOMs and active power filters (APFs) to overcome the aforementioned drawbacks are the cascaded H-bridge (CHB) multilevel converters-based [4]. The advantages of CHB converters include low harmonic distortion, reduced number of switches, suppression of switching losses, modularity and good scalability [5]-[6]. In order to provide a good trade-off among good tracking of references variables, harmonic performance, switching frequency, commutation losses and the balancing of the DC-link voltages, several control and modulation techniques can be applied to CHB converters, such as: pulse width modulation (PWM), space vector modulation (SVM), phase shift carrier - PWM (PSC-PWM) and model based predictive control (MBPC) [7]-[9]. MBPC has recently gained the attention of the research community like a control technique in power converters and drives [1], mainly because

the advantage of it focuses on its flexible feature, since it is possible to adapt to different control requirements modifying only a cost function.

This paper proposes a novel DC-link balance technique for a 7-level CHB converter-based STATCOM system with MBPC, using for this purpose a switcher of redundant vectors (SRV) and the equations that represent the dynamics of the system, additionally to achieve a reactive power compensation and decreased current harmonics. In order to illustrate the benefits of the proposed control a series of simulations have been carried out. The simulation results have been analyzed and compared with the obtained using a conventional MBPC.

This paper is organized as follows: Section II presents the three-phase three-wire 7-level CHB multilevel STATCOM topology. In Section III is discussed the proposed MBPC technique with SRV for DC-link voltage balance. Section IV discusses the simulation results and provides a comparative analysis with the conventional MBPC technique. Finally, concluding remarks are presented in the last section of the paper.

II. DESCRIPTION OF THE CHB STATCOM TOPOLOGY

Fig. 1 shows the three-phase three-wire 7-level CHB converter-based STATCOM topology studied. Three cascade H-bridge modules per phase, called cells, with an independent DC-link per cell compose the STATCOM system. Since each cell contains four switching devices, four switching signals ($s\phi_{ij}$) are needed to achieve the desired output voltage ($v_i^\phi = F_i^\phi v_{dc}$) for each cell, where ϕ represents the phase (a, b or c), i the cell number in the corresponding phase (1, 2 or 3), j the switching device corresponding to the cell “ i ” (1, 2, 3 or 4), v_{dc} the voltage of the capacitor and F_i^ϕ the switching function. Because of there are combinations that cause a short circuit in the DC-link of the cells, only two activation signals and their complementary levels are used, i.e., if $s\phi_{11} = 1$, then $s\phi_{12} = 0$ and if $s\phi_{11} = 0$, then $s\phi_{12} = 1$, similarly for $s\phi_{i3}$ and $s\phi_{i4}$. One switching state ($\eta \in \{1, 2, \dots, \varepsilon\}$) of one phase in particular, where ε is the total of possible switching states, which depends of the number of cells per phase (n_c),

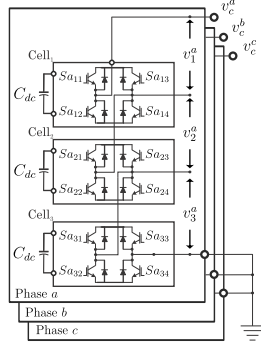


Fig. 1. Three-phase 7-level CHB converter-based STATCOM system.

is represented by a switching vector (S_{ij}^ϕ) that contains $2n_c$ activation signals (s_{ij}) of such phase (note that the capital “S” is related to the vector and the small “s” is related to the signal). Finally, the output voltage for each phase of the STATCOM is $v_c^\phi = F_s^\phi v_{dc}$, where $F_s^\phi = \sum_{i=1}^3 F_i^\phi$ denotes the switching function for each phase.

A. Continuous time-domain model

Fig. 2 shows one phase (ϕ) of the CHB converter-based STATCOM connection. The dynamic model of the circuit configuration can be obtained by using Kirchhoff’s circuit laws. It is assumed, for modeling purposes, a balanced electric power grid. Applying Kirchhoff’s voltage law for the AC side of the STATCOM, the following equation is obtained:

$$\frac{di_c^\phi}{dt} = \frac{v_s^\phi}{L_f} - \frac{R_f}{L_f} i_c^\phi - \frac{F_s^\phi v_{dc}}{L_f} \quad (1)$$

where R_f is the parasitic (series) resistance of the inductor L_f .

B. Discrete-model for predictive control

Forward-Euler discretization method is used to obtain the predictive model from the continuous time-domain model represented by (1), which provides the following equation:

$$i_c^\phi(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^\phi(k) + \frac{T_s}{L_f} \{v_s^\phi(k) - v_c^\phi(k)\} \quad (2)$$

where k identifies the actual discrete-time sample, T_s is the sampling time, and $i_c^\phi(k+1)$ are the predictions of the STATCOM phase currents made at sample k .

III. PROPOSED MODEL BASED PREDICTIVE CONTROL WITH SWITCHER OF REDUNDANT VECTORS

Fig. 3 shows the block diagram of the proposed model based predictive control with SRV applied to the three-phase three-wire 7-level CHB converter-based STATCOM system. The current references are generated for reactive power compensation from the measured variables, as will be shown next.

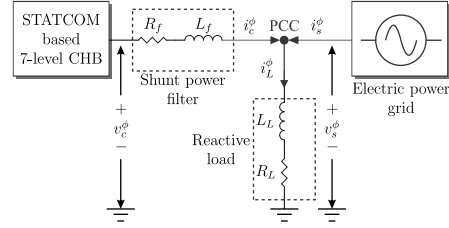


Fig. 2. STATCOM, load and electric grid connected through the PCC.

A. Reactive power compensation

The instantaneous active and reactive power references are obtained from the Clarke’s transformation approach in $\alpha - \beta$ reference frame by using the following transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (3)$$

Applying (3), the $\alpha - \beta$ current references at the AC side of the STATCOM are obtained as follows:

$$\begin{bmatrix} i_{c\alpha}^* \\ i_{c\beta}^* \end{bmatrix} = \frac{1}{(v_{s\alpha})^2 + (v_{s\beta})^2} \begin{bmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (4)$$

where the superscript (*) denotes the reference variables and P_c^* and Q_c^* are the instantaneous active and reactive power references, respectively. In order to allow a unitary power factor at the grid side and considering which ideally the STATCOM do not absorb any active power, the instantaneous power references can be written as $P_c^* = 0$ and $Q_c^* = -Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha}$, being Q_L the instantaneous reactive load power to be compensate by the CHB converter-based STATCOM system. Finally, the STATCOM phase currents references used in the optimization process are:

$$[i_c^{a*} \ i_c^{b*} \ i_c^{c*}]' = \mathbf{T}^{-1} [i_{c\alpha}^* \ i_{c\beta}^* \ 0]' \quad (5)$$

where the superscript (') indicates the transposed matrix.

B. Cost function and optimization process

The cost function is defined as a quadratic measure of the predicted error, as follows:

$$g^\phi = \|ei_c^\phi(k+1)\|^2 \quad (6)$$

being $ei_c^\phi(k+1)$ the STATCOM current errors at the AC side.

The optimization is performed by search over the 7 possible levels of the control action and selects the optimal level or switching function F_s^ϕ ($-3, -2, -1, 0, 1, 2$ or 3) that minimizes the defined cost function represented by (6). During the optimization process, both the cost function and the predictive model must be computed 7 times at each sampling period to guarantee optimality. Then, the first optimal vector is applied.

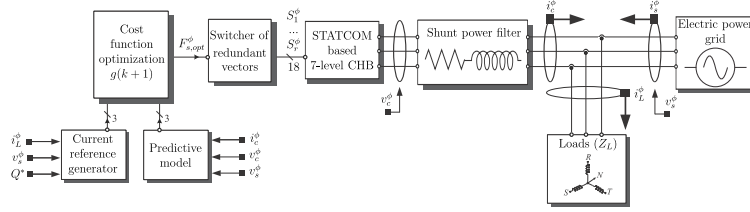


Fig. 3. Block diagram of the proposed model based predictive control with switcher of redundant vectors.

C. Switcher of redundant vectors

An obvious solution to the voltage balancing problem is to commute the cells that are charging capacitors and those that are discharging capacitors [8], while maintaining the same optimal level (voltage output). Each optimal level has an amount of redundant vectors (r), which is variable depending of the level, as is shown in Table I.

TABLE I
AMOUNTS OF REDUNDANT VECTORS FOR EACH LEVEL

Voltage output ($\times v_{dc}$)	-3	-2	-1	0	1	2	3
Redundant vectors (r)	1	6	15	20	15	6	1

In order to charge and discharge all capacitors simultaneously, for one phase in particular, all redundant vectors for such phase are sequentially applied during a period until the next sampling instant, with a duty cycle given by the following equation:

$$\tau^\phi = \frac{T_s}{r} \quad (7)$$

To simplify the algorithm, is selected $r = 20$ for all levels, thus, the vectors of the levels with fewer amount of redundant vectors are reapplied until to complete a sampling period.

IV. SIMULATION RESULTS

A MatLab/Simulink simulation environment has been developed to analyze the performance of the proposed control technique applied to the three-phase 7-level CHB converter-based STATCOM system, considering the electrical parameters shown in Table II. The performance of the proposed control technique is compared with the results obtained by a conventional MBPC, in both cases considering a 20 kHz of sampling frequency.

Fig. 4 shows a simulation results of the proposed control technique under steady-state and transient conditions. Fig. 4 (upper) shows a step in the instantaneous reactive power reference where it is possible to notice the effect of reactive power compensation (from 3,000 to 1,500 VAR after 0.04 s). Moreover, Fig. 4 (bottom), shows the tracking current dynamic performance for a step change of the reactive power reference. It can be observed from the simulation results a fast dynamic response during the transient.

TABLE II
PARAMETERS DESCRIPTION

PARAMETER	7-Level CHB STATCOM		
	SYMBOL	VALUE	UNIT
Grid frequency	f_e	50	Hz
Grid voltage	v_s	310.2	V
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	114	V
DC-link capacitance	C_{dc}	21	mF
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	50	μs
Active power reference	P_r^*	0	W
Ideal reactive power reference	Q_r^*	$-Q_L$	VAR

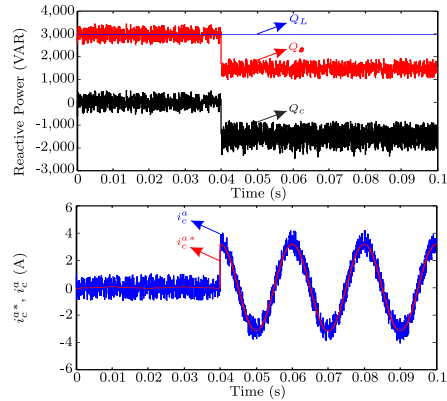


Fig. 4. CHB STATCOM steady-state and transient response: (upper) reactive power compensation, (bottom) tracking current.

Fig. 5 shows a comparison analysis between the proposed predictive control and the conventional MBPC considering:

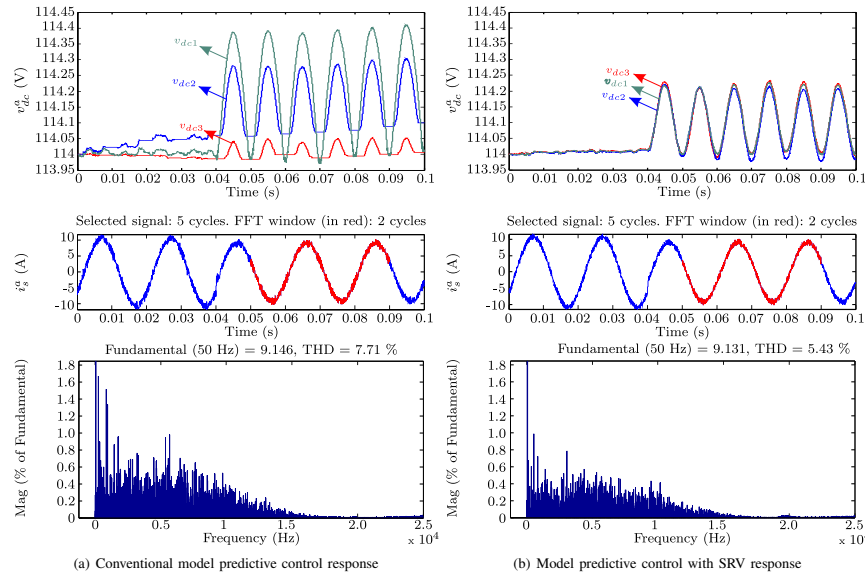


Fig. 5. Comparison performance considering: (upper) the voltage evolution on the capacitors, (middle) the grid current and (bottom) the THD of the grid current.

(upper) the voltages on the capacitors of the phase a (middle) the grid current of the phase a and (bottom) the THD of the analyzed grid current. As shown in Fig. 5 (b) a better performance is obtained in terms of voltage ripple and a simultaneous charge/discharge process on the capacitors. Furthermore, the improvement obtained in the THD performance parameter is about 30% (a drop from 7.71% to 5.43%) using the proposed method, considering the interval where the reactive power is compensated (after 0.04 s).

V. CONCLUSION

In this paper, a MBPC with SRV applied to the three-phase three-wire 7-level CHB STATCOM has been proposed. The simulation results confirm the capability of the proposed control technique to compensate the instantaneous reactive power and shows that it is possible to increase the performance in terms of THD, compared with the results obtained by the conventional MBPC. A comparative simulation results performed with reference to the conventional MBPC also show improvements relative to balance voltages in the DC-links.

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Model Based Predictive Current Control for a Three-Phase Cascade H-Bridge Multilevel STATCOM Operating at Fixed Switching Frequency

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Abstract—The absence of modulator in model based predictive control technique for different converter topologies generates a variable switching frequency that produces high frequency harmonics and higher stress on the power semiconductor devices. In this paper, a novel model based predictive control strategy with a fixed switching frequency applied to a three-phase cascade H-bridge multilevel STATCOM is introduced with the aim to increase the performance of classical model predictive control. Simulation results show increased performance of the proposed control method in terms of current waveform total harmonic distortion.

Index Terms—Cascade H-bridge converter, fixed switching frequency, model based predictive control.

NOMENCLATURE

CHB	Cascade H-bridge.
MBPC	Model based predictive control.
MSE	Mean squared error.
PCC	Point of common coupling.
STATCOM	Static synchronous compensator.
THD	Total harmonic distortion.

I. INTRODUCTION

The major reasons for the growing interest in the use of MBPC technique are the evolution of data processing capabilities of the digital signal processors, its nonlinear operation, fast dynamic response and simplicity to represent different control objectives by a cost function. Classical MBPC method consists in use a precise mathematical model of the system to have an accurate prediction of the behavior of the controlled variables, where the prediction is carried out for each possible switching state, that in power converters, there are always a limited number of valid switching states. Next, an optimization process uses this information to evaluate a defined cost function for each prediction to provide the control action that minimizes such cost function. Then, the control action selected is applied in the next sampling time [1]. The classic MBPC has the particularity to provide a variable switching frequency, due to the absence of modulator. In terms of power quality, not only the spread spectrum and the high frequency harmonics are shown in the output waveforms but also the

high stress on the power semiconductor devices. In order to solve these issues, a novel approach for different topologies and its applications has been presented: three-phase active rectifier [2], two-level voltage source inverters [3]-[5], direct matrix converters [6], [7], active power compensators [8], neutral pointed clamping converters [9] and 7-level CHB back-to-back converter [10]. Of all of the different topologies and their applications, the CHB multilevel converters-based is one of the most commonly used and an attractive topology due to their modularization, extensibility, control simplicity and high-quality output [11], [12].

The purpose of this paper is to use a MBPC strategy with fixed switching frequency, in order to control a three-phase CHB 7-level STATCOM. Noteworthy that the proposal is not innovative, however, still now is not recorded in the literature neither simulations results nor experimental results of this control technique applied to three-phase CHB 7-level converter for STATCOM applications. The proposed control approach consists in to include a modulation stage in the optimization algorithm of the classical MBPC, to generate the duty cycles for two active switching states and one null switching state which are applied to the CHB 7-level STATCOM using a switching pattern procedure. An optimization process considering a defined cost function allows calculating the duty cycles of each switching state.

II. CHB CONVERTER-BASED STATCOM MODEL

Fig. 1 shows the three-phase 7-level CHB converter-based STATCOM coupled to the power grid and the load through a shunt power filter (L_f - R_f), connected in the PCC. The STATCOM is composed by three cells H-bridge per phase with an independent DC-link for each cell. All DC-link buses have the same voltage v_{dc} and the same capacitance C_{dc} values. Each cell contains four switching devices which are activated with digital signals $s\phi_{ij}$, being ϕ the corresponding phase (a , b or c), i the cell number (1, 2 or 3) and j the switching device (1, 2, 3 or 4). With the purpose of avoiding a short-circuit in the DC-link, the signals $s\phi_{i1}$ and $s\phi_{i3}$ are complementary to $s\phi_{i2}$ and $s\phi_{i4}$ respectively. Then, to adjust

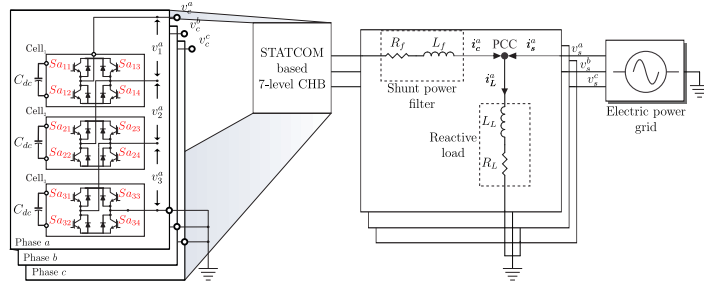


Fig. 1. Three-phase 7-level CHB converter-based STATCOM system connection.

the output voltage v_c^ϕ , only $2n_c = 6$ signals are needed. Each phase have $n_c = 3$ number of cells and $\varepsilon = 2^{2n_c} = 64$ possible switching states. Furthermore, each switching state corresponds to a switching function $F_s^\phi = \sum_{i=1}^{n_c} F_i^\phi$, where F_i^ϕ is the switching function for the cell i , whose possible values are shown in Table I.

TABLE I
SWITCHING FUNCTIONS FOR THE CELL “ i ”

$s_{\phi i1}$	$s_{\phi i3}$	$s_{\phi i2}$	$s_{\phi i4}$	F_i^ϕ
1	0	0	1	+1
1	1	0	0	0
0	0	1	1	0
0	1	1	0	-1

The output voltage can be synthesized as a function of the DC-link voltage v_{dc} and the switching function F_s^ϕ as:

$$v_c^\phi = F_s^\phi v_{dc} \quad (1)$$

Using Kirchhoff's circuit laws, the continuous time-domain model of the CHB converter-based STATCOM is:

$$\frac{di_c^\phi}{dt} = \frac{v_s^\phi}{L_f} - \frac{R_f}{L_f} i_c^\phi - \frac{v_c^\phi}{L_f} \quad (2)$$

where i_c^ϕ is the current injected by the CHB converter-based STATCOM and v_s^ϕ the grid voltage.

The discrete time-domain model is obtained by using the forward-Euler discretization method:

$$i_c^\phi(k+1) = \left(1 - \frac{R_f T_s}{L_f}\right) i_c^\phi(k) + \frac{T_s}{L_f} \{v_s^\phi(k) - v_c^\phi(k)\} \quad (3)$$

being T_s the sampling time, k identifies the actual discrete-time sample and $i_c^\phi(k+1)$ are the predictions of the STATCOM phase currents made at sample k .

III. PROPOSED PREDICTIVE CONTROL WITH FIXED SWITCHING FREQUENCY

The classical MBPC technique uses the predictive model represented by (3) to predict the behavior of the future states

of all possible switching states. Then, the predicted errors for current tracking are calculated as follows:

$$ei_c^\phi(k+1) = i_c^{\phi*}(k+1) - i_c^\phi(k+1) \quad (4)$$

where the superscript (*) indicates a reference variable.

The cost function (for each phase ϕ) is defined as a quadratic measure of the predicted error, as follows:

$$g^\phi = \|ei_c^\phi(k+1)\|^2 \quad (5)$$

where $\|\cdot\|$ denotes the magnitude of the variable.

Finally, the switching state that generates the minimum value of the defined cost function is selected by an optimization process clearly described in the Algorithm 1. This optimum switching state is applied in the next sampling time during the whole switching period.

Algorithm 1 Optimization algorithm of the classic MBPC

1. Initialize $g_{opt}^a := \infty, g_{opt}^b := \infty, g_{opt}^c := \infty, \eta := 0$
2. Compute $i_c^{a*}(k+1)$, $i_c^{b*}(k+1)$ and $i_c^{c*}(k+1)$
3. **while** $\eta \leq \varepsilon$ **do**
4. Compute $i_c^a(k+1)$, $i_c^b(k+1)$ and $i_c^c(k+1)$
5. Compute $ei_c^a(k+1)$, $ei_c^b(k+1)$ and $ei_c^c(k+1)$
6. Compute g^a , g^b and g^c
7. **if** $g^a < g_{opt}^a$ **then**
8. $g_{opt}^a \leftarrow g^a$, $F_{s,opt}^a \leftarrow F_{s,\eta}^a$
9. **end if**
10. **if** $g^b < g_{opt}^b$ **then**
11. $g_{opt}^b \leftarrow g^b$, $F_{s,opt}^b \leftarrow F_{s,\eta}^b$
12. **end if**
13. **if** $g^c < g_{opt}^c$ **then**
14. $g_{opt}^c \leftarrow g^c$, $F_{s,opt}^c \leftarrow F_{s,\eta}^c$
15. **end if**
16. $\eta := \eta + 1$
17. **end while**

A. Classical vs. proposed MBPC

The main difference between the proposed method and the classical MBPC, is that the proposed method proceeds as

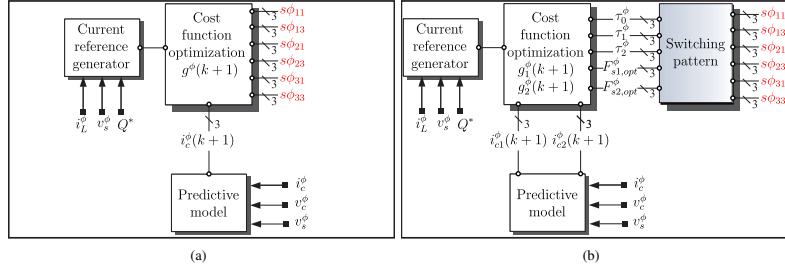


Fig. 2. Block diagram for: (a) the classic MBPC, (b) the proposed MBPC at fixed switching frequency.

space vector modulation. In space vector modulation, each sector is defined by two adjacent vectors (and one null vector), nonetheless, in this work, the “sectors” are defined by two consecutive active (or no-null) states and one null state (please refer to Appendix). For simplicity, always $\eta = 1$ is used as null state (where η is the state number, defined in the Appendix). Then, the first sector is the one between switching state number $\eta = 2$ and switching state number $\eta = 3$, the second sector, the one between switching state number $\eta = 3$ and switching state number $\eta = 5$, and so on. The two optimum states are chosen by an optimization process that evaluates the predicted errors separately for each prediction and are applied during specified times, being their duty cycles inversely proportional to the respective cost functions.

The block diagram of the classic MBPC method and the proposed method are shown in Fig. 2, where the switching pattern block is highlight.

B. Cost function optimization

The new cost function (for each phase ϕ) for the proposed method is defined as the sum of the cost functions $g_{1,2}^\phi$ defined by (5) whose respective weighting factors are the duty cycles $\tau_{1,2}^\phi$ for the two active states, leaving the equation as:

$$g^\phi = \tau_1^\phi g_1^\phi + \tau_2^\phi g_2^\phi \quad (6)$$

The switching state that generates the lowest value of the cost function must be applied higher time, i.e., the duty cycle must be inversely proportional to the cost function. The duty cycles for the two active switching states and one null switching state are calculated by solving:

$$\begin{aligned} \tau_0^\phi &= K^\phi / g_0^\phi \\ \tau_1^\phi &= K^\phi / g_1^\phi \\ \tau_2^\phi &= K^\phi / g_2^\phi \\ \tau_0^\phi + \tau_1^\phi + \tau_2^\phi &= 1 \end{aligned} \quad (7)$$

where τ_0^ϕ correspond to the duty cycle of a null state which is evaluated only one time and K^ϕ is the constant of proportionality.

The expressions of the duty cycles for each switching state are given solving (7) for K^ϕ as:

$$\begin{aligned} \tau_0^\phi &= g_1^\phi g_2^\phi / (g_0^\phi g_1^\phi + g_1^\phi g_2^\phi + g_0^\phi g_2^\phi) \\ \tau_1^\phi &= g_0^\phi g_2^\phi / (g_0^\phi g_1^\phi + g_1^\phi g_2^\phi + g_0^\phi g_2^\phi) \\ \tau_2^\phi &= g_0^\phi g_1^\phi / (g_0^\phi g_1^\phi + g_1^\phi g_2^\phi + g_0^\phi g_2^\phi) \end{aligned} \quad (8)$$

Being the turn-on times (T_0^ϕ , T_1^ϕ and T_2^ϕ) the products of multiplying the duty cycles (τ_0^ϕ , τ_1^ϕ and τ_2^ϕ) by the sampling time, respectively.

Finally, the optimization process (for each phase ϕ) is illustrated in Algorithm 2.

Algorithm 2 Optimization algorithm of the proposed method

1. Initialize $g_{opt}^\phi := \infty$, $\eta := 0$
2. Compute $i_c^*(k+1)$
3. Compute $i_{c0}^\phi(k+1)$
4. Compute $ei_{c0}^\phi(k+1)$
5. Compute $g_0^\phi = g_0^\phi(k+1)$
6. **while** $\eta \leq \varrho$ **do**
7. Compute $i_{c1}^\phi(k+1)$ and $i_{c2}^\phi(k+1)$
8. Compute $ei_{c1}^\phi(k+1)$ and $ei_{c2}^\phi(k+1)$
9. Compute $g_1^\phi = g_1^\phi(k+1)$ and $g_2^\phi = g_2^\phi(k+1)$
10. Compute τ_0^ϕ , τ_1^ϕ and τ_2^ϕ
11. Compute $g^\phi = \tau_1^\phi g_1^\phi + \tau_2^\phi g_2^\phi$
12. **if** $g^\phi < g_{opt}^\phi$ **then**
13. $g_{opt}^\phi \leftarrow g^\phi$
14. Compute T_0^ϕ , T_1^ϕ and T_2^ϕ
15. $F_{s1,opt}^\phi \leftarrow F_{s1,\eta}^\phi$, $F_{s2,opt}^\phi \leftarrow F_{s2,\eta}^\phi$
9. **end if**
10. $\eta := \eta + 1$
11. **end while**

C. Switching pattern

At the end of the optimization process, the two optimum active switching states ($F_{s1,opt}^\phi$ and $F_{s2,opt}^\phi$) and the one null switching state are applied during their respective turn-on

times using the switching pattern procedure that is shown in Fig. 4, similar to [3], [4].

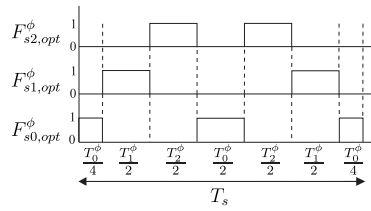


Fig. 3. Switching pattern for the optimal switching states.

D. Current reference generator

Using the following Clarke's transformation matrix:

$$\mathbf{T} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (9)$$

the instantaneous $\alpha - \beta$ current references are:

$$\begin{bmatrix} i_c^{\alpha*} \\ i_c^{\beta*} \end{bmatrix} = \frac{1}{(v_s^{\alpha})^2 + (v_s^{\beta})^2} \begin{bmatrix} v_s^{\alpha} & v_s^{\beta} \\ v_s^{\beta} & -v_s^{\alpha} \end{bmatrix} \begin{bmatrix} P_c^* \\ Q_c^* \end{bmatrix} \quad (10)$$

where the instantaneous active and reactive power references ideally are:

$$\begin{aligned} P_c^* &= 0 \\ Q_c^* &= -Q_L \end{aligned} \quad (11)$$

being $Q_L = v_{s\alpha} i_{L\beta} - v_{s\beta} i_{L\alpha}$ the instantaneous reactive load power to be compensate.

Finally, the STATCOM phase currents references used in the optimization process are:

$$[i_c^{\alpha*} \ i_c^{\beta*} \ i_c^{c*}]' = \mathbf{T}^{-1} [i_c^{\alpha*} \ i_c^{\beta*} \ 0]' \quad (12)$$

where the superscript $(\cdot)'$ indicates the transposed matrix.

IV. SIMULATION RESULTS

In order to validate the effectiveness of the proposed method, simulation results in Matlab/Simulink environment were carried out, considering the electrical parameters shown in Table II. The performance of the proposed method are compared with the results obtained with the classical MBPC implementation, in both cases considering a 25 kHz of sampling frequency.

A good current tracking is presented in Fig. 4 (upper), having a reduction in the MSE from 0.4206 A to 0.3207 A. Moreover, in Fig. 4 (bottom) it is possible to notice how the instantaneous reactive power is compensated ($Q_c = -Q_L$). The big spikes are consequence of the application of the null vector in the switching pattern.

TABLE II
PARAMETERS DESCRIPTION

Electric power grid			
PARAMETER	SYMBOL	VALUE	UNIT
Grid frequency	f_e	50	Hz
Grid voltage	v_s	310.2	V
7-Level CHB STATCOM			
Filter resistance	R_f	0.09	Ω
Filter inductance	L_f	3	mH
DC-link voltage	v_{dc}	154	V
Load parameters			
Load resistance	R_L	23.2	Ω
Load inductance	L_L	55	mH
Predictive control parameters			
Sampling time	T_s	40	μs
Simulation step	—	1	μs

A comparison analysis between the proposed method and the classical MBPC is shown in Fig. 5 considering: (upper) the switching pattern, (middle) the output voltages of the STATCOM and (bottom) the THD of the analyzed output voltage. As shown in Fig. 5 (b) a more sinusoidal output voltage v_o^a is obtained with respect to the output voltage than in Fig. 5 (a) due to the switching pattern procedure. Furthermore, the operation at fixed switching frequency produces a more concentrated spectrum in exchange of a higher THD parameter of the output voltage (due to the way in which the sectors were defined).

Additionally, considering the interval 0.05 to 0.09 s, Fig. 6 shows the improvement obtained in the THD performance parameter of the grid current, that is about 65% (a drop from 6.61% to 2.32%) using the proposed method.

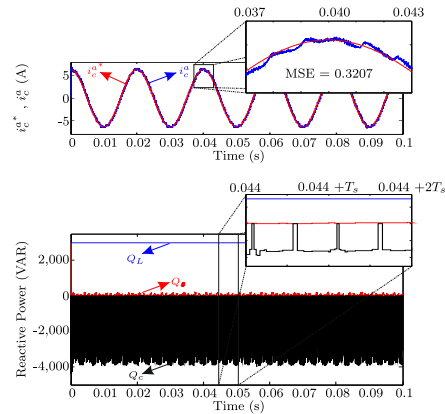


Fig. 4. CHB STATCOM response: (upper) current tracking, (bottom) reactive power compensation.

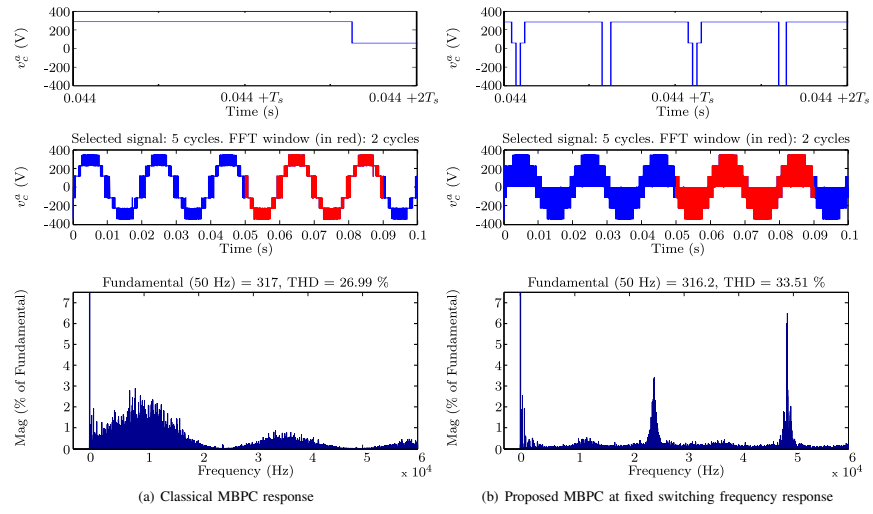


Fig. 5. Comparison performance considering: (upper) the switching pattern of the output voltage of the STATCOM obtained (middle) the output voltage of the STATCOM and (bottom) the THD of the output voltage.

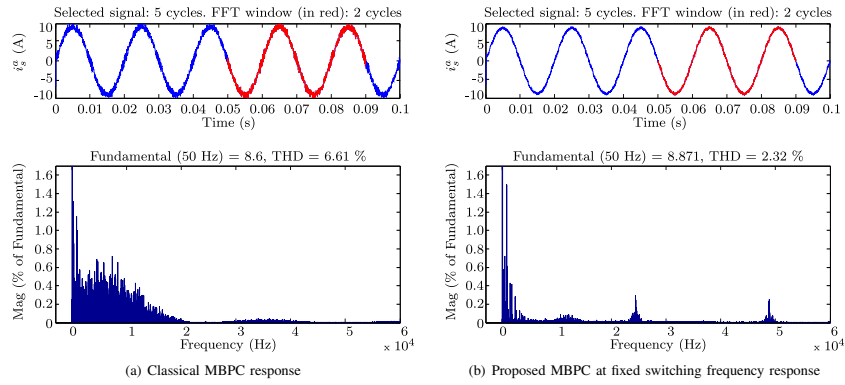


Fig. 6. Comparison performance considering: (upper) the grid current and (bottom) the THD of the grid current.

V. CONCLUSION

In this paper, a MBPC operating at fixed switching frequency applied to the three-phase CHB 7-level STATCOM has been proposed. From the simulation results it is possible to confirm a good capability of the proposed control technique to compensate the reactive power and better performance in terms of THD and MSE, compared with the results obtained by the classical MBPC. A comparative simulation results performed with reference to the classical predictive control also show improvements relative to the output voltage waveform.

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APPENDIX

TABLE III
SWITCHING FUNCTIONS FOR A THREE-PHASE 7-LEVEL CHB
CONVERTER-BASED STATCOM SYSTEM

$S\phi_{\eta}$						η	$F_{s,\eta}^{\phi}$
$s\phi_{11}$	$s\phi_{13}$	$s\phi_{21}$	$s\phi_{23}$	$s\phi_{31}$	$s\phi_{33}$		
0	0	0	0	0	0	1	0
0	0	0	0	0	1	2	-1
0	0	0	0	1	0	3	1
0	0	0	0	1	1	4	0
0	0	0	1	0	0	5	-1
0	0	0	1	0	1	6	-2
0	0	0	1	1	0	7	0
0	0	0	1	1	1	8	-1
0	0	1	0	0	0	9	1
0	0	1	0	0	1	10	0
0	0	1	0	1	0	11	2
0	0	1	0	1	1	12	1
0	0	1	1	0	0	13	0
0	0	1	1	0	1	14	-1
0	0	1	1	1	0	15	1
0	0	1	1	1	1	16	0
0	1	0	0	0	0	17	-1
0	1	0	0	0	1	18	-2
0	1	0	0	1	0	19	0
0	1	0	0	1	1	20	-1
0	1	0	1	0	0	21	-2
0	1	0	1	0	1	22	-3
0	1	0	1	1	0	23	-1
0	1	0	1	1	1	24	-2
0	1	1	0	0	0	25	0
0	1	1	0	0	1	26	-1
0	1	1	0	1	0	27	1
0	1	1	0	1	1	28	0
0	1	1	1	0	0	29	-1
0	1	1	1	0	1	30	-2
0	1	1	1	1	0	31	0
0	1	1	1	1	1	32	-1
1	0	0	0	0	0	33	1
1	0	0	0	0	1	34	0
1	0	0	0	1	0	35	2
1	0	0	0	1	1	36	1
1	0	0	1	0	0	37	0
1	0	0	1	0	1	38	-1
1	0	0	1	1	0	39	1
1	0	0	1	1	1	40	0
1	0	1	0	0	0	41	2
1	0	1	0	0	1	42	1
1	0	1	0	1	0	43	3
1	0	1	0	1	1	44	2
1	0	1	1	0	0	45	1
1	0	1	1	0	1	46	0
1	0	1	1	1	0	47	2
1	0	1	1	1	1	48	1
1	1	0	0	0	0	49	0
1	1	0	0	0	1	50	-1
1	1	0	0	1	0	51	1
1	1	0	0	1	1	52	0
1	1	0	1	0	0	53	-1
1	1	0	1	0	1	54	-2
1	1	0	1	1	0	55	0
1	1	0	1	1	1	56	-1
1	1	1	0	0	0	57	1
1	1	1	0	0	1	58	0
1	1	1	0	1	0	59	2
1	1	1	0	1	1	60	1
1	1	1	1	0	0	61	0
1	1	1	1	0	1	62	-1
1	1	1	1	1	0	63	1
1	1	1	1	1	1	64	0



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Análisis de la eficiencia de un Puente-H basado en tecnología SiC-MOSFET para aplicaciones de alta frecuencia y media potencia

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RESUMEN

El presente trabajo muestra el diseño de un esquema para un controlador de puente-H completo basado en la tecnología SiC-MOSFET utilizado para aplicaciones de alta frecuencia y media tensión. A modo de cuantificar la eficiencia del diseño se realizaron mediciones de las pérdidas por conmutación y las pérdidas por conducción que presentan los semiconductores basados en los resultados experimentales obtenidas en laboratorio con la plataforma experimental montada para tal efecto.

INTRODUCCIÓN

Con el desarrollo de la tecnología de los semiconductores de potencia así como el aumento significativo en la potencia de cómputo de los microprocesadores, las capacidades del manejo de la energía y la velocidad de conmutación de los dispositivos de potencia han mejorado considerablemente presentando mayor eficiencia a frecuencias más elevadas.

Actualmente con los avances en fabricación de nuevos dispositivos semiconductores basados en tecnologías de carburo de silicio (SiC), han permitido ampliar las opciones a la hora de seleccionar los dispositivos de conmutación para aplicaciones de potencia. Las características de estos nuevos semiconductores permiten mejorar la eficiencia del sistema, trabajar bajo tensiones de bloqueo mayores (del orden de los 1200V en algunos SiC MOSFETs), además tienen como características importantes su reducida pérdida de conducción así como la de conmutación y frecuencias de conmutación más elevadas en comparación a los IGBT.

El presente trabajo se basa en el desarrollo de una plataforma experimental formado por un sistema Puente-H completo, sus circuitos de acondicionamiento de señales y controladores, utilizando una frecuencia de conmutación del orden de los 100Khz.

MATERIALES Y MÉTODOS

En la Figura 1 se observa el sistema experimental implementado para cuantificar la eficiencia de la celda puente-h diseñado. El sistema incluye la celda puente-H con sus circuitos de acondicionamientos, controladores y DC-Link. Para cuantificar la eficiencia del diseño se procede a medir las tensiones y corrientes de drenador en los SiCMOSFET para diferentes valores de potencia de salida entregada a la carga. Para las pruebas experimentales se utilizó una carga tipo RL con valores de $R=20\text{ Ohm}$ y $L=10\mu\text{H}$, el DC-Link se implementó mediante fuentes de alimentación de DC.

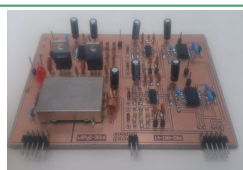
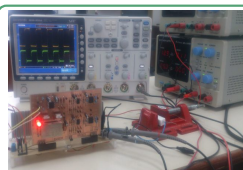


Figura 1: (Izq.) Plataforma experimental utilizada para realizar las mediciones. (Der.) Placa de control diseñado para el disparo de los SiC-MOSFET.

RESULTADOS

En la Figura 2 se observa las señales utilizadas para medir los intervalos de tiempo de las transiciones presentadas por las señales VDS e ID, además se observa los resultados de los cálculos de eficiencia. La imagen termográfica muestra las temperaturas de cada semiconductor del puente-H, con los siguientes valores: SP1=75,3°C, SP2=72,1°C, SP3=80,6°C, SP4=70,1°C.

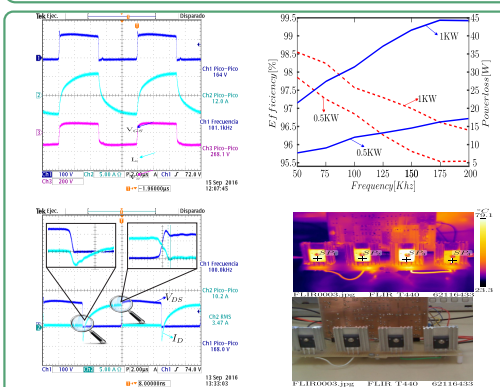


Figura 2: (Izq. Sup.) Señales de salida Vo, Io y VGS. (Izq. Inf.) Señales VDS e ID de los SiC-MOSFET. (Der. Sup.) Eficiencia y pérdidas de potencia. (Der. Inf.) Imagen termográfica del puente-H.

CONCLUSIONES

Considerando los resultados obtenidos se observan que las pérdidas por conmutación aumentan con la frecuencia mientras que las pérdidas por conducción disminuyen con el aumento de la frecuencia. El diseño responde adecuadamente dentro del rango de frecuencias de operación comprendida entre los 50Khz y 200Khz, obteniéndose un rendimiento del 98% al 95% conforme aumenta la frecuencia.

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We confirm that the student ALFREDO RENAULT LOPEZ has been a full-time student at University of Trento from 26/04/2017 (arrival date) to 31/07/2017 (end date) under the ERASMUS+ agreement with the University of Trento.

The courses have been taught in/The research activities have been developed in English (*specify language/s*).

Date 31.07.2017

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20161842905/2017

Student ID number: 191569

We hereby certify that **RENAULT LOPEZ ALFREDO** born in ASUNCIÓN - PARAGUAY - on 07/08/1990, has been enrolled at the University of Trento as an incoming exchange student on a.y. 2016/2017, from 26/04/2017 to 31/07/2017, in the framework of the ERASMUS+ International Credit Mobility, with the UNIVERSIDAD NACIONAL DE ASUNCIÓN (Paraguay).

This is to certify that the student passed the following exams with marks expressed in a scale from 18 to 30.

DSS	EXAM	Credits	MARK	Honour	KEY
NN	Research Activity	15	AP		
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TO WHOM IT MAY CONCERN

This is to certify that the student **Alfredo RENAULT LOPEZ** has worked on his research project at the Department of Civil, Environmental and Mechanical Engineering of the University of Trento under my supervision during the period 27/04/2017 - 31/07/2017
Number of hours: 3-month (27/04/17 to 31/07/17)

Title of the project: ANALISIS DEL CONTROL PREDICTIVO DE CORRIENTE APLICADO AL FILTRO ACTIVO DE POTENCIA BASADO EN CONVERTIDORES EN CONFIGURACION PUENTE H DE DOS NIVELES

The work corresponds to 15 ECTS

Brief evaluation: During the 3-month (26/04/17 to 31/08/17) at the University of Trento, in Department of Civil, Environmental and Mechanical Engineering, Alfredo Renault Lopez has developed the following activities:

- presentation of the paper "Modulated Model Predictive Current Control for H-Bridge Two-Level Single Phase Active Power Filters STATCOM", at the conference "IEEE Conference on Industrial Electronics and Applications", (ICIEA2017) presented the 18 - 20 June 2017, in Siem Reap, Cambodia.
- a paper to will present at conference "Modulated Model Predictive Current Control for H-Bridge Two-Level Three Phase Active Power Filters STATCOM" accepted in "IEEE Southern Hemisphere Power Electronics Conference" (SPEC2017) 4 to 7, December, Puerto Varas, Chile.
- thesis of Master "Análisis del control predictivo de corriente aplicado al filtro activo de potencia basado en convertidores en configuración puente-H de dos niveles" to be presented in Paraguay.

The student has developed these activities, during its international mobility, with good scientific result.

The overall judgment of the work done is very good.

Yours faithfully,

prof. Maurizio Fauri



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