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Extraction and Compensation of Dominate Harmonics in High Power Hybrid Active Power Filters for HVDC Applications

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Abstract: - For nonlinear loads beyond 10 MW, the hybrid active power filters are not cost effective due to high bandwidth, high ratting and low efficiency; therefore, the passive filters are typically used for harmonic filtering of high power nonlinear loads. On the other hand, the passive filters compensation characteristics are affected by utility system impedance variations. The HVDC systems that use the highest power nonlinear converters, use the 12- pulse converters in which the 11^{th} and 13^{th} harmonics are the dominate harmonics. In the conventional links, these harmonics are compensated by tuned passive filters. However, the hybrid active power filters that can inject the certain components, don't need to have high bandwidth and have acceptable efficiency. This paper presents a new control scheme for a shunt hybrid parallel active power filter (HPAF) intended for high power application to meet IEEE 519 recommended harmonic standards. The instantaneous value of those harmonics are extracted separately by abc to dq transformation (SRF) and the active inductor reference voltage which have to be applied to the voltage source inverter of hybrid active power filter, are made by active inductance concept. In addition, it controls the dc voltage of the capacitor in the dc side of HPAF. Finally, the resultant vector, which is obtained from control unit, is applied to produce the gating signals of the HAPF converter by space vector modulation (SVM) method.

Key-Words: - Active filter, SRF, HVDC, Harmonic detection, Active inductance

1 Introduction

Theoretically, the 11^{th} and 13^{th} harmonics in the AC side current spectrum of a conventional HVDC link are the lowest harmonics. Passive L-C filters have been traditionally preferred harmonic filtering solution mainly for their high efficiency and simplicity and low cost particularly for low power application [1] – [5]. These filter's filtering characteristics are affected by component tolerance and varying system impedance. Further more, a stiff system poses great difficulties for L-C filter design since a sharp and precise tuning will be required to sink a significant percentage of the load harmonic current. Considering all these problems, L-C filters may not meet the IEEE 519 standard [6]. Hybrid active filter with a shunt passive filter and a small-rating active filter in series with the passive filter [5], have been proposed for harmonic isolation of large rectifier loads with a simple control strategy based on a proportional controller and detection of total source current distortion obtained after subtraction of the fundamental component [7]. A proportional controller, however cannot provide satisfactory attenuation of source current harmonics if the passive filter is not tuned properly at the dominate load harmonics and a broad-band high-frequency active filter inverter is required [8], [9]. On the other hand, due to their bandwidth requirement, their applications are limited to nonlinear loads below 10 MW [10]. For nonlinear loads beyond 10 MW, hybrid active filter systems implemented with PWM inverters are not cost effective due to the high band width and high rating requirement. Passive L-C filters are usually used for this level of loads. However, as stated previously, using L-C filters may not meet the IEEE 519 standards [6].

For large 12-pulse rectifier, a selective AF control system has been proposed in [7] with full isolation at 5^{th} and 7^{th} harmonic frequencies achieved with square wave voltage injection into dominate harmonic (11^{th} and 13^{th}) passive filters. For the detection and control of 5^{th} and 7^{th} harmonics, low-pass filters and proportional pulse integral (PI) controllers were applied in reference frames rotating synchronously with corresponding harmonic space vectors. This technique was successfully used in vector controlled AC drives for many years and later applied for active filters [11]. However, a single synchronous reference (SRF) is appreciated for balanced three phase systems just for it tracks only positive- or negative-sequence vectors. For tracking both sequence harmonic vectors in unbalanced three-phase systems, double cascaded SRFs have been

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proposed [12], resulting in complex AF control systems, especially when tracking several spectral components is required.

In this paper the author have proposed the dominate harmonic active filter (DHAF) intended for high power nonlinear load beyond 10 MW particularly for HVDC [13] , [14]. The proposed DHAF controller achieves dynamically varying negative or positive inductances at single or multiple dominant harmonic frequencies, based on the generalized impedance converter principle [15]. It also achieves harmonic isolation at the dominate harmonic frequencies, for example, at the 11th and 13th frequencies for conventional HVDC converters.

2 Parallel Hybrid Active Filter System Implementation

The parallel hybrid active filter topology consists of 11th and 13th $L-C$ tuned passive filter branches as parallel and one active filter connected in series with them, as shown in Figs. 1. Alternatively, in some low power applications, there can be one active filters connected in series with entire passive filter system and also optional high-pass filters, as given in [4]. In this case, however, the active filter inverter has to be implemented by a high frequency PWM inverter. Multi-tuned filter performance can be achieved by tuning the passive filter at dominate harmonic frequency by inverter output filter inductor and with active filter connected in series to provide tuning at second dominate harmonic frequency. However, in high power nonlinear loads this can not be done practically; because, in this case the tuned filter shows considerable impedance at other frequencies and consequently injection of these harmonics increases the active filters converter size.

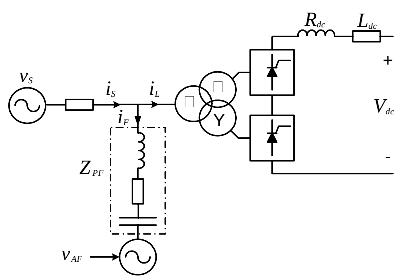

Fig. 1. System configuration.

The proposed variable inductance controller based on parallel hybrid active power filter system with eleventh and thirteenth passive filters can effectively provide harmonic compensation of the load and prevent passive filter overloading by a current limiting feature, in presence of ambient harmonic loads and supply of voltage harmonics. A cost optimization between inverter device current and voltage rating and their cost and the coupling transformer cost can be done based on the manufacturer's cost structure for the devices (IGBT's or GTO thyristors) compared to that of the transformers. The coupling transformer and its ratio also has an impact on dc bus capacitance C_{dc} , dc bus voltage V_{dc} , and inverter output filter inductor $L_{f_{inv}}$.

3 System Configuration and Principle of Operation

3-1 Selective reference frame harmonic detector unit

Active filters can be classified according to their operation principles as a load-current detection type or a source-current detection type [16]. In conventional load current detection methods, the generation of the active filter current reference is usually based on the harmonic detection of the load currents, using the well-known instantaneous power theory, time domain correlation techniques, etc. Using this solution, however due to the time domain approach, the delay of the APF current control causes incorrect compensation and unwanted remaining harmonics in the line currents. This effect is dramatic especially when a fully digital control implementation is used, since the achievable performance may decrease below an acceptable level.

The selective reference frame harmonic detector unit (SRFHD) is outlined in Fig. 2 where the three phase system is assumed to be without neutral wire, so that all three phase quantities are expressed in d-q coordinates; note however, that the forthcoming description can be easily extended to three phase four-wire systems [11]. The SRF controller achieves its hth harmonic isolation by using closed loop control on the hth harmonic component of the load current where h is the order of the generic harmonic to be compensated and ω_0 is line angular frequency. The block diagram in Fig. 2 represents only a general solution which ensures detection of the selected harmonic independently of any hypothesis on load symmetry. For specific loads such as diode or thyristor rectifiers the characteristic harmonics have positive and/or negative sequence components, for example, in balanced HVDC 12-pulse converters the 11th harmonic has only negative-sequence component and the 13th harmonic has only positive component.

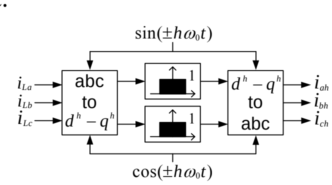

Fig. 2. SRF harmonic detector unit.

Three phase current component at arbitrary frequency can be converted into dc signals by filtering the current transformed into SRF coordinates. Thus, SRF based harmonic detector can be used for tracking sinusoidal currents and this technique is common use in ac motor drives. The single SRF harmonic detector of Fig. 2 can be used for controlling either a positive- or a negative-sequence component at synchronous frequency. For each sequence the related rotating frame is selected in SRF. For this propose the positive sign in Fig. 2. is used in abc to dq transformation of positive sequence components and consequently the negative sign is sued in abc to dq transformation of negative sequence components. Therefore, the negative and the positive signs are used to dq to abc transformation of positive and negative sequences respectively. The three phase load currents are measured and transformed into the synchronous reference frame ($d^h - q^h$ axis) rotating at the h th harmonic as follows:

$$\begin{bmatrix} i_d^h \\ i_q^h \end{bmatrix} = T_h.\begin{bmatrix} i_{La} & i_{Lb} & i_{Lc} \end{bmatrix}^T \quad (1)$$

where T_h is the SRF transformation matrix to $d^h - q^h$ rotating reference frame [11]. If the ω_0 is known preciously, in the synchronously rotating $d^h - q^h$ reference frame, the component at the fundamental frequency are transformed to dc quantities and other components are transformed to non-dc quantities and undergo a frequency shift of $h \times f_0\, Hz$ in the spectrum which f_0 is the fundamental frequency of the currents. The SRF controller extracts dc quantities by a low pass filter (LPF) and hence it is insensitive to phase errors. This is a significant advantage of the SRF controller because most other controllers will introduce considerable phase errors at fundamental and harmonic frequencies.

3-2 SRF Based Controller for Implementation of Variable Inductance

The SRF controller is implemented by analog and digital hardware as opposed to a DSP based implementation for ease of debugging in the field installation. The SRF controller implementation is sensitive to dc offset and gains. This requires a flat or constant gain of the LPF up to the cutoff frequency. Effective heterodyning is possible due to wide separation of the fundamental rotating frequency at dc and the closest harmonic in the synchronous reference frame and reduce the sensitivity of the LPF to phase and amplitude error. Amplitude accuracy is achieved by maximally flat Butterworth LPF. The fundamental frequency of the ac system which is used in SRF unit often is determined by PLL block. The operation of PLL is based on phase detection of the signal. Since the same procedure is applied to dominate harmonic detection of load current and the component detection of output current of active filter, any small deviation on fundamental frequency detection which is used in SRF transformations, doesn't lead to considerably error on results. On the other hand, the frequency variation in ac networks particularly in ac side of HVDC links is as low as $\pm 0.5\,Hz$; therefore, the transformation of the 11th and 13th harmonics in $d^h - q^h$ reference frame would not be dc components if the fundamental frequency of ac system is not estimated or calculated preciously instead, they will be transformed to the non-dc signals with a few frequency. In fact, if Δf is the estimation error of the fundamental frequency, the desired transformed components in rotating $d^h - q^h$ reference frame will be ac signals with $h\Delta f$ frequency and hence the flat characteristic of the low pass filter is needed to have an acceptable output. Therefore, the low-pass filters for the eleventh and thirteenth harmonic filter currents and load currents are implemented by sixth order Butterworth low-pass filters and, for filter fundamental current , by a fourth order Butterworth low-pass filter. Consequently the cutoff frequency has been chosen 20 Hz for all cases. These lead to the response is designed to be maximally flat so far as possible.

The SRF controller concept as shown in Fig. 3, is used to implement a dynamically varying either negative or positive active inductance L_{AF_h}. The SRF controller generates the desired active inductor inverter reference voltage at a specified frequency, which is then synthesized either by a three phase PWM, as shown in Fig. 3. The implementation of the variable inductance is explained for an active filtering application and can be applied similarly for other applications. The active filter inverter currents i_{ca}, i_{cb}, i_{cc} are measured and transformed into a synchronously rotating $d^h - q^h$ reference frame, at the specified h th harmonic frequency of synthesis of L_{AF_h}, given by i_d^h and i_q^h. This is achieved by unit vectors $\cos(h\omega t)$ and $\sin(h\omega t)$ which can be derived from the phase-locked loop (PLL) on the passive filter terminal voltage v_f, as shown in Fig. 1. The active inductor inverter reference voltage $v_{L_{AF}}^h$ is given by (2).

$$v_{\text{inv}}^*\Big|_{h\text{th harmonic}} = L_{AF_h} \frac{di_{\text{inv}}}{dt}\Big|_{h\text{th harmonic}} \quad (2)$$

where L_{AF_h} is the positive or negative active

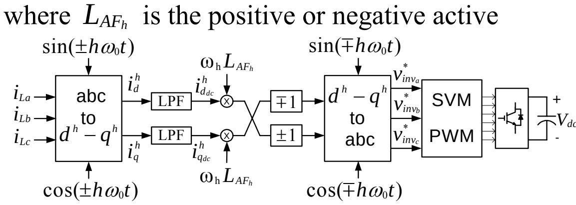

Fig. 3. SRF controller for variable inductance.

inductance to be synthesized at hth harmonic frequency.

The differentiation of current in steady state is achieved by interchanging i_q^h and i_d^h currents, q^h- and d^h- axis currents, and multiplying by ω_h and then the resulted values in the d^h- and q^h-axes are multiplied by the desired active inductance L_{AF_h} as follows :

$$\begin{bmatrix} v_d^h \\ v_q^h \end{bmatrix} = L_{AF_h} h\omega_0 \begin{bmatrix} 0 & -k \\ k & 0 \end{bmatrix} \begin{bmatrix} i_d^h \\ i_q^h \end{bmatrix} \quad (3)$$

where k is 1 for positive sequence components and -1 for negative sequence components. The resulting voltages in the d^h- and q^h-axes are then transformed to three phase stationary frame inverter reference voltages, $v_{\text{inv}_a}^*$, $v_{\text{inv}_b}^*$ and $v_{\text{inv}_c}^*$ (4).

$$\begin{bmatrix} v_{inv_a} \\ v_{inv_b} \\ v_{inv_c} \end{bmatrix} = T_h^{-1} \begin{bmatrix} v_d^h \\ v_q^h \end{bmatrix} \quad (4)$$

This operation is valid because of the orthogonal relationship between the current and voltage for an inductor so achieves the differential operator function of 90° phase rotation and multiplication by ω_h for a single frequency [17]. The inverter reference voltages can be synthesized by a space vector based PWM inverter, as shown in Fig. 3. The SRF controller implementation for variable positive or negative active inductance facilitates synthesis of different L_{AF_h} values at multiple frequencies by superposition of desired active inductor voltages. This is possible because the SRF controller for implementation of variable inductance generates active inductor inverter reference voltages $v_{\text{inv}_a}^*$, $v_{\text{inv}_b}^*$ and $v_{\text{inv}_c}^*$ as shown in Fig. 4. For example, different $L_{AF_{11}}$ and $L_{AF_{13}}$ values can be synthesized simultaneously by adding the active inductor it voltages corresponding to $L_{AF_{11}}$ and $L_{AF_{13}}$. Further, should be noted that the direct generation of inverter reference voltages allows the use of voltage based PWM schemes which can be implemented by space vector PWM schemes [17], [18] or simple and constant switching frequency sine-triangle. Voltage based PWM schemes require lower inverter bandwidth than conventional current regulated PWM schemes hence, these schemes are the preferred solution for high power applications.

The inverter reference voltages generated by the eleventh and thirteenth SRF controllers v_{inv}^{11} and v_{inv}^{13}, respectively, may be superimposed to generate active filter inverter reference voltage for the topology as shown in Fig. 5. In fact, a single active filter inverter emulates a multi-tuned filter. However, a PWM inverter is required to provide multiple tuning at the eleventh and thirteenth harmonic frequencies.

4 DC bus voltage controller

The power converter is operated as a harmonic resistor, it will consume real power. This real power is injected into the DC capacitor of a power converter, and then the voltage of DC capacitor will arise. A dc bus controller is required to regulate dc voltage of capacitor, V_{dc}, and to compensate the inverter power losses, this is achieved by generating a small inverter fundamental voltage v_{fund} in phase with the fundamental positive sequence reactive filter current i_{f1}, as shown in Fig. 3 and in expression (5). Hence, the dc capacitor of the power converter is regarded as an energy buffer to absorb the harmonic real power and regenerate the fundamental real power to the mains.

$$v_1(t) = k_{dc} i_{h1}(t) \quad (5)$$

The active inductance L_{AF_h} based control generates an active filter inverter voltage $v_{L_{AF}}^{11} + v_{L_{AF}}^{13}$

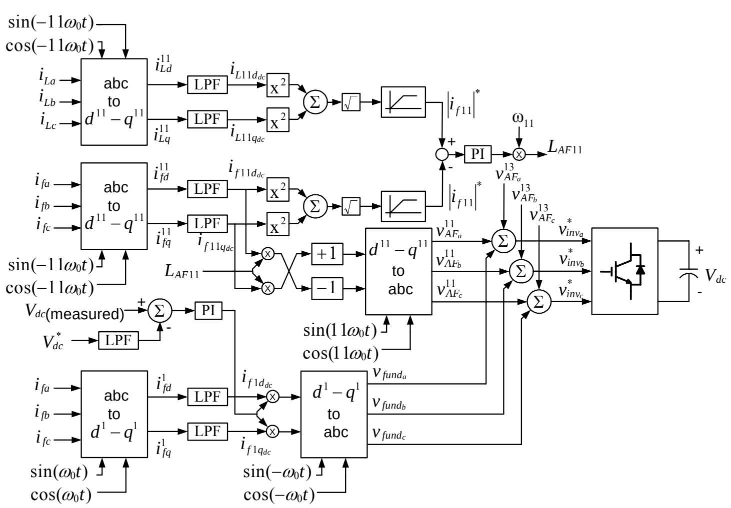

Fig. 4. System configuration of SRF controller.

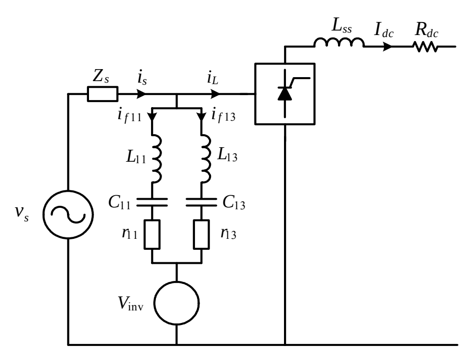

Fig. 5. System configuration of SRF controller.

orthogonal to the related harmonic current in the passive filter and ensures no real power transfer at harmonic frequencies, under all supply and load conditions. Hence, supply voltage harmonics do not impact on real power transfer and, consequently, do not require dc bus power balancing, unlike other parallel hybrid active filters controlled to provide harmonic isolation [14]. The fundamental passive filter current i_{f1} is extracted by SRF controller at the fundamental frequency. The measured harmonic filter branch currents i_{fa} , i_{fb} and i_{fc} are transformed into a positive sequence synchronously rotating $d^h - q^h$ reference frame at the fundamental frequency, given by i^1_{fq} and i^1_{fd} . The dc components in the SRF are extracted by low-pass filters as indicated by $i_{f1q\,dc}$ and $i_{f1d\,dc}$ and correspond to fundamental positive sequence filter current. The measured dc bus voltage V_{dc} is low-pass filtered and compared with nominal reference dc bus voltage V^*_{dc} and the error is fed into a PI controller. The output is multiplied by extracted dc values i^1_{fq} and i^1_{fd} and transformed at fundamental frequency to generate three phase inverter voltage references given by v_{fund_a} , v_{fund_b} and v_{fund_c} . This is added to inverter voltage references generated by the variable inductance controller gives the total active filter inverter reference voltages v_{inv_a} , v_{inv_b} and v_{inv_c} , as shown in Fig. 3 (6).

$$v^*_{\mathrm{inv}(a,b,c)} = v^{11}_{AF(a,b,c)} + v^{13}_{AF(a,b,c)} + v_{fund\,(a,b,c)} \quad (6)$$

5 PSCAD/EMTDC Simulation Results of Parallel Hybrid Active Power Filter System

The proposed hybrid parallel active power (HPAF) filter was studied using PSCAD/EMTDC software package. It used to compensate the two dominate ac current harmonics, 11th and 13th harmonics, in rectifier side of the 12 pulses Benchmark model of HVDC link. The performance of the proposed system is documented in Figs. 6-10. Fig 6. shows the measured current of rectifier converter. It consist 11th , 13th , 23 th , 25th and . . . characteristics harmonics. The 11th and 13th components are two dominate harmonics. and 13th harmonics by SRF harmonic detector unit.

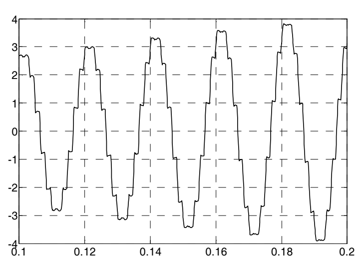

Fig. 6. Rectifier converter current.

Fig. 7 shows the SRF extracted components for 11th Fig. 8 shows the active inductor inverter reference voltages for 13th , 11th harmonics and their total consequently to be applied to passive filter by VSI using SVM PWM switching method.

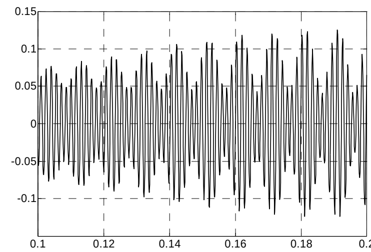

Fig. 7. extracted components for 11th and 13th harmonics.

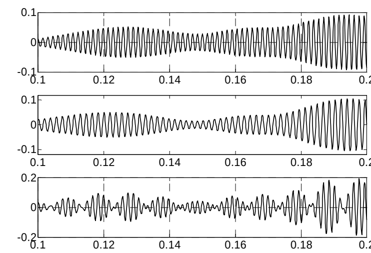

Fig. 8. The active inductor inverter reference voltages for 13th , 11th harmonics and their total consequently.

Fig. 9 shows the dc voltage across the active filter capacitor which controlled by fundamental component of the inverter voltage reference.

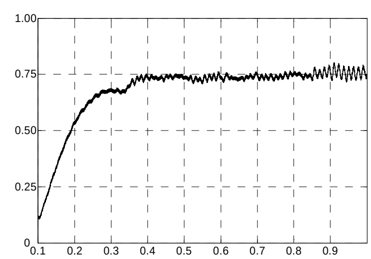

Fig. 9. V_{dc} across the active filter capacitor.

Fig. 10 shows the proposed active filter response when the transferred active power filter through HVDC link is increasing. This is the injected current of active filter VSI which consist the 11th and 13th harmonics components and also the fundamental

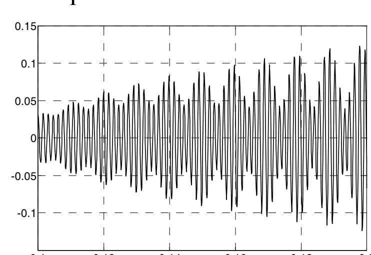

Fig. 10. The active filter response.

component which restores the dc voltage across the inverter capacitor.

6 Conclusion

A hybrid active power filter with selective active filter control is introduced in this paper. This filter allows applying a low rating active filter with reduced switching frequency which is particularly useful in high power applications. Harmonic current controlling based on SRF is used in the targeted harmonic frequency tracking filter. This approach gives good synchronization, even for highly distorted reference voltage and no PLL is required in this approach. The concept and synthesis of dynamically varying positive and negative active inductance based on SRF theory is general and has potential for other applications. A single active filter provides multituning by selectively synthesizing multiple active inductances at specified dominate harmonic frequencies. This controller is simple and can be implemented by analog digital hardware. The simulation results show that knowing the system's exact frequency is not necessary due to the flat characteristic of the used low pass filter for components less than cut-off frequency in harmonic detection method.

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