

Analysis of Steady State and Dynamic Performance of a Static Synchronous Compensator (STATCOM)

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Abstract - This paper presents some steady state and dynamic performance characteristics of a twelve-pulse STATCOM (Static Synchronous Compensator) using the Electromagnetic Transient Program EMTP/ATP (Alternative Transients Program). The twelve-pulse STATCOM and its compensation characteristics are analyzed. For steady state studies, the analysis of possible resonance due to the harmonics generated by the converter switching is presented. During the dynamic performance analysis, both frequency and time responses of the STATCOM are evaluated. Moreover, an interesting analysis of the converter linearity is presented, showing that the gain between the reactive power reference and the reactive power generated by the STATCOM is linear.

Keywords: FACTS, STATCOM, System Dynamic Performance, Reactive Shunt Compensation.

I. INTRODUCTION

In 1988, Hingorani [1] introduced the FACTS (Flexible AC Transmission System) concept. With FACTS technology devices, which are based on Power Electronics, it would be possible to control electrical systems variables like active and reactive power flow, shunt or series impedance, voltage in a specific bus, etc. Today, the FACTS technology is a reality. It involves a set of controllers that provide more flexibility to AC electrical power systems.

The first generation of FACTS devices was based in high power thyristors. Various examples of practical applications of these devices can be found around the world, including TCSCs (Thyristor Controlled Series Capacitors) and SVCs (Static Var Compensators) [2].

With the development of self-commutated (turn-off and turn-on capability) semiconductor devices, the second generation of FACTS equipment took place. These equipments are based on Voltage Source Converters (VSCs) and use switches like GTO (Gate Turn-off Thyristor) and IGBT (Insulated Gate Bipolar Transistor). The GTO is, until now, the power semiconductor component that has the highest voltage and current ratings (6 kV, 6 kA). In the near future, the IGCT (Integrated Gate Commutated Thyristor) will, probably, appear as a real option for practical applications.

The Static Synchronous Compensator (STATCOM) is one of the most important FACTS devices based on the use

of self-commutated semiconductors. Ekström et al. [3] compares a conventional SVC with a STATCOM and shows the superiority of the STATCOM.

The STATCOM has been used to improve power system stability, voltage regulation and reactive power compensation [4], [5], [6]. The STATCOM hardware is based on Voltage Source Converters (VSC), a capacitor in its DC side and the converter controller. It is connected to a power system through a step-up transformer.

This paper presents steady-state and dynamic performance characteristics of a twelve-pulse STATCOM. The studies were performed using the Electromagnetic Transient Program EMTP/ATP (Alternative Transients Program).

Initially, the STATCOM synthesis using two six-pulse voltage source converters (Fig. 1) and its shunt compensation characteristics are presented. A computer model was implemented using the EMTP/ATP, including a relatively simple electric network circuit and a detailed controller model, which was developed using TACS (Transients Analysis of Control Systems).

For the steady-state performance evaluation the following studies were done: presentation of the voltage, current and harmonic converter characteristics and analysis of possible resonances due to harmonics generated by the converter switching. It is shown that the harmonics generated by the converter may introduce some resonance problems depending on the frequency characteristics of the electric system as seen from the point of connection of the STATCOM.

The dynamic performance evaluation investigates both the frequency and time responses of the STATCOM. It is shown that it can respond to frequencies up to 20 Hz,

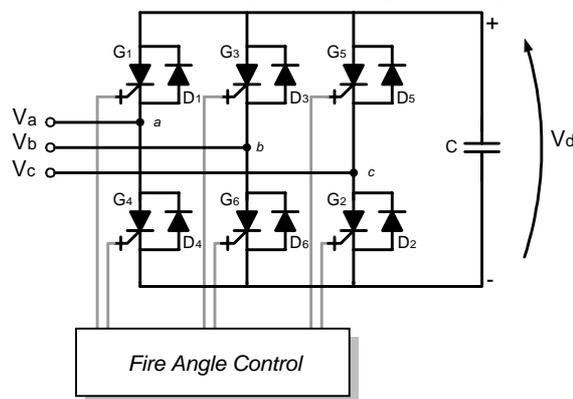


Fig. 1. Six-pulse converter

presenting a peak in the gain Bode diagram for frequencies around 10 Hz. Moreover, the linearity of the compensation characteristics was analyzed. It is shown that the gain (relation between the output reactive power and the reference reactive power) of this device is linear for every single frequency that may be considered.

II. THE STATIC SYNCHRONOUS COMPENSATOR

The basic three-phase six-pulse converter is shown in Fig. 1. Six valves compose this converter and each valve is made up of a GTO with a diode connected in anti-parallel.

On the DC side, the converter is connected to a voltage source. If only reactive power compensation is required, this source can be substituted by a small charged capacitor [7], [8]. The converter is connected to the AC grid through a coupling step-up transformer.

In a three-phase six-pulse VSC, each GTO is fired and blocked one time per line voltage cycle. In this case, each GTO in a single branch conducts during a half-cycle (180 degrees) of the fundamental period. The combined pulses of each leg are 120 degrees phase-shifted. In this way, the converter produces a balanced set of three voltages, as illustrated in Fig. 2. These voltages have harmonic components with frequencies of $[6k \pm 1] \cdot f$, where f is the fundamental system frequency and $k = 1, 2, 3 \dots$

In order to reduce the harmonic contents at the output voltages, the number of pulses can be increased, forming a multi-pulse configuration. Multi-pulse converters are composed by n ($n = 2, 4, 8, \dots$) six-pulse bridges connected in parallel on the same DC bus and interconnected in series through transformers on the AC side. Depending on the

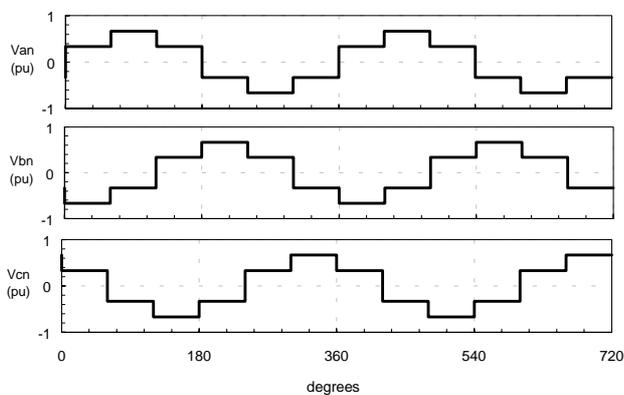


Fig. 2. Six-pulse converter waveforms

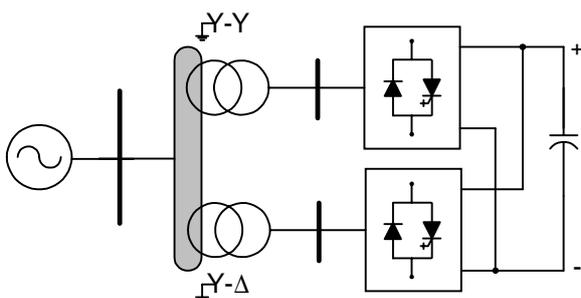


Fig. 3. Twelve-pulse configuration

number of pulses, these transformers and its connections can become very complexes.

Two six-pulse bridges can be connected, forming a twelve-pulse converter. In this case, the first converter is connected with a wye-wye transformer and the second one with a wye-delta transformer, as shown in Fig. 3. Moreover, the delta-connected secondary of the second transformer must have $\sqrt{3}$ times the turns compared to the wye-connected secondary. If the pulse train of one converter is shifted by 30 degrees with respect to the other and if the primary sides of the transformers are connected in series, the total output voltage on the AC side will be the sum of the individual voltages in each transformer, as shown in Fig. 4. This figure shows the voltages in the secondary of each transformer and the total twelve-pulse output voltage.

In this manner, it is possible to eliminate low order harmonics. The total output voltage of a twelve-pulse STATCOM has harmonic components with frequencies of $[12k \pm 1] \cdot f$, where f is the fundamental system frequency and $k = 1, 2, 3 \dots$

The twelve-pulse STATCOM model was implemented using the EMTP/ATP program. The implemented control system is designed to control the reactive current injected by the converter into the AC system. This is done by playing with the converter output voltage. If the converter voltage is higher than the system voltage, a capacitive current will flow from the system to the STATCOM. On the other hand, if the converter voltage is smaller than the system voltage, an inductive current will flow from the system to the STATCOM.

In order to control the converter output voltage, the DC voltage should be controlled. So, the DC capacitor should be charged or discharged, increasing or decreasing the STATCOM output voltage when compared to the system voltage. It means that, to change the converter reactive characteristic, an active power flow between the converter and the system is necessary.

The control system acts then to provide an advance or a delay on the pulse train to the GTOs. In this manner, an active power flow is injected from or into the converter, decreasing or increasing the voltage across the capacitor terminals, respectively.

The complete STATCOM control system scheme implemented on EMTP/ATP is shown in Fig. 5. The line currents (compensation currents) are measured and

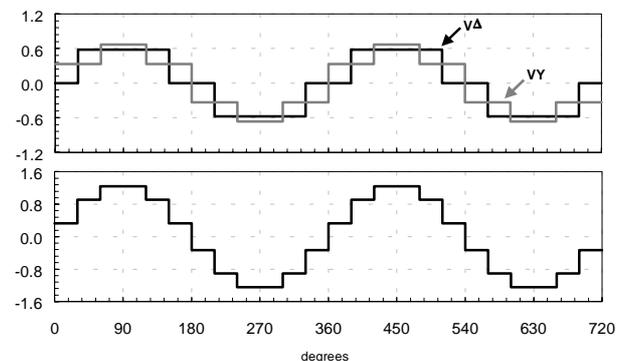


Fig. 4. Twelve-pulse converter waveforms

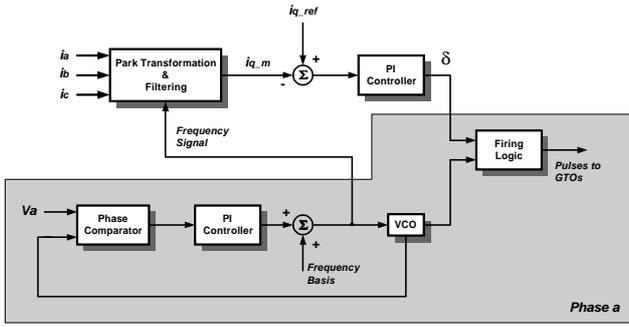


Fig. 5. Reactive current control scheme

transformed to the synchronous reference frame (Park Transformation or dq0 Transformation). Both real (direct) and imaginary (quadrature) currents are calculated, but only the reactive portion (imaginary) is injected into the control system. There is a filtering process to eliminate high frequencies and the second harmonic (120 Hz) present at the measured reactive current. The high frequencies appear due to the switching and the second harmonic is generated by the coordinate conversion procedure.

The measured value (after filtering) is compared with a reference value, generating an error signal. This signal is the input of a PI (Proportional-Integral) controller. The output of the controller gives the phase angle δ necessary to produce a power flow between the STATCOM and the AC system, changing the converter output voltage level.

If the error between the reactive current of the converter and the reactive current reference does not exist ($i_{q,m} = i_{q,ref}$), the phase angle should be zero ($\delta = 0$). However, if $i_{q,m} < i_{q,ref}$, then $\delta > 0$ and the STATCOM voltage lags the AC system voltage, causing a real power flow into the converter. Consequently, the DC capacitor will be charged, increasing the STATCOM output voltage, which produces a growth of the converter reactive current until $i_{q,m} = i_{q,ref}$. When this situation is reached, the signal error will be zero and the control system will be stabilized. If $i_{q,m} > i_{q,ref}$, the opposite process will occur. Fig. 5 also shows a PLL (Phase-Locked Loop) circuit. The PLL is necessary to maintain the synchronism between the pulses to the GTOs gates and the AC system voltage. Besides, the Park Transformation requires the use of correct voltage phase angles.

The STATCOM model implemented has the characteristics described in Table 1. This table shows some technical parameters of the converter, including the DC capacitor voltage and energy when there is no compensation. In this situation, the AC STATCOM voltage is equal to the AC bus voltage.

Tab. 1 STATCOM Parameters

Parameter	Value
AC nominal voltage	18 kV
Fundamental frequency	60 Hz
Total apparent power	50 MVA
Number of pulses	12
DC capacitor size	2000 μ F
DC Voltage without compensation	11,54 kV
DC energy without compensation	132,25 kJ

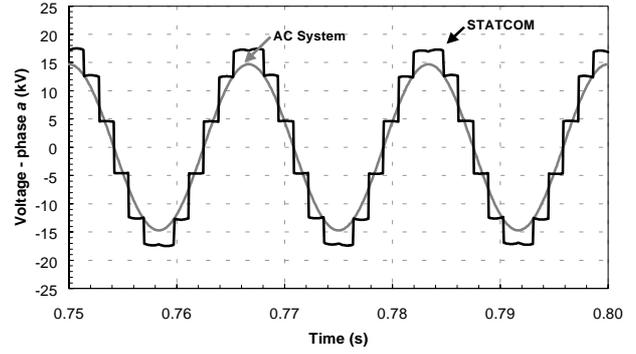


Fig. 6. Steady state operation: voltages

The simulations were performed using only the converter connected to a stiff AC source (infinite bus). This configuration was chosen to guarantee that any other phenomenon would not interfere on the performance analysis of the STATCOM.

III. STEADY STATE PERFORMANCE

Several simulations were performed in order to evaluate the steady-state characteristics of the twelve-pulse STATCOM. Fig. 6 shows a simulation result, when the converter operates with a capacitive characteristic. This figure shows the AC system voltage and the STATCOM output voltage. As can be seen, the converter voltage is higher than the AC bus voltage. Moreover, there is no significant phase difference between the two voltages. It means that, except for losses, only reactive power is being compensated.

The harmonic spectrum of the STATCOM output voltage is depicted in Fig. 7. As expected, the voltage contains harmonic components with frequencies of $[12k \pm 1] \cdot f$, where f is the fundamental system frequency (60 Hz) and $k = 1, 2, 3 \dots$. The most significant harmonic frequency is 660 Hz (11th harmonic). However, its magnitude does not reach 10% of the fundamental component amplitude.

Fig. 8 shows the line current of the STATCOM for the same simulation. It is interesting to observe that the current has a particular waveform characteristic due to the switching. The current has the same harmonic frequencies of the converter output voltage.

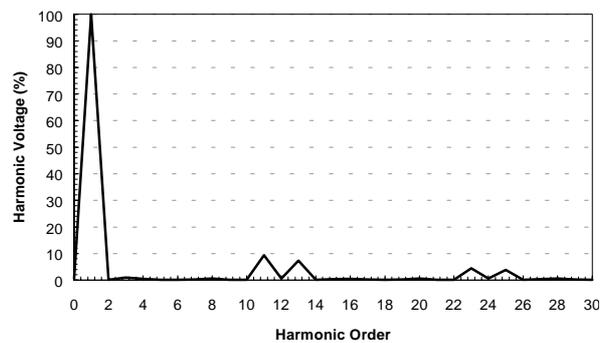


Fig. 7. Steady-state operation: voltages harmonic components

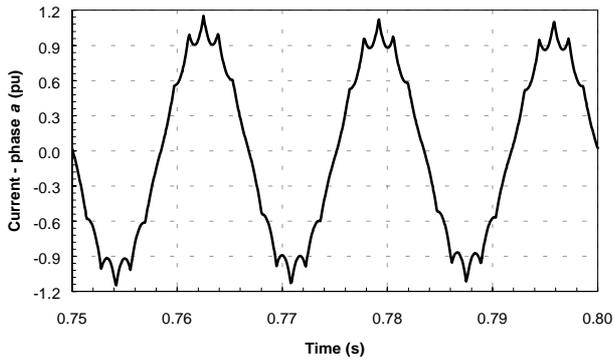


Fig. 8. Steady state operation: AC current

A. Analysis of Possible Resonance Problems

The presence of FACTS controllers in power systems can produce some resonance problems due to the presence of harmonics components generated by these devices. In order to exemplify this kind of problem, a simulation was performed using a simple electric network circuit, depicted in Fig. 9. An ideal AC source (230 kV), a transmission line (101.2 km) and a transformer connecting the line and the STATCOM transformer compose the simulated system. In this figure, the converter and its transformer are represented in a simplified way.

A detailed study of the operating characteristics of the system, as seen from the point of connection of the STATCOM, for different frequencies, was done. This study has shown that there is a low impedance at 780 Hz, configuring a series resonance in the system. If this frequency was not tuned to a natural harmonic frequency produced by the STATCOM, no problem should be expected. However, the converter behaves as a harmonic

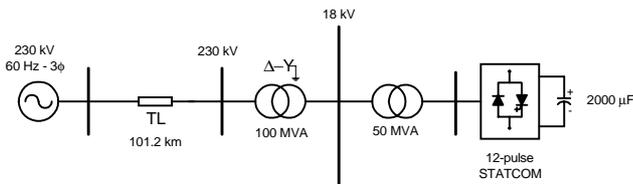


Fig. 9. Simulated system with resonance problems

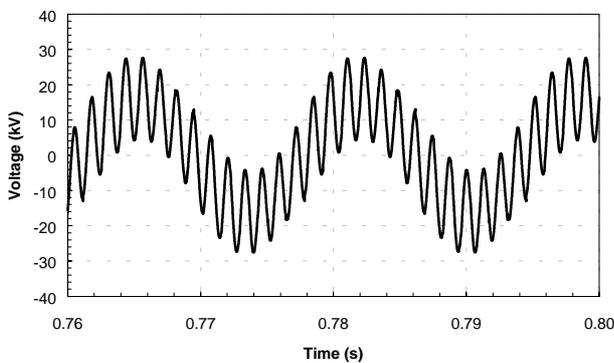


Fig. 10. Resonance problems: 18 kV bus voltage

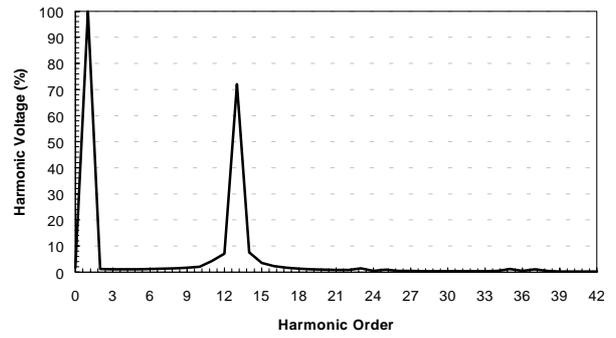


Fig. 11. Resonance problems: harmonic voltages

source at 780 Hz. So, harmonic amplification occurs, as illustrated in Fig. 10. This figure shows the voltage at the 18 kV bus.

The harmonic spectrum of this voltage is shown in Fig. 11. As can be seen, the harmonic voltage in 780 Hz reaches more than 70% of the magnitude of the fundamental frequency voltage.

IV. DYNAMIC PERFORMANCE

For the correct use of the STATCOM it is necessary to analyze and understand its dynamic performance behavior. Therefore, in this section, the step and frequency responses of the STATCOM will be analyzed. Moreover, an analysis of the linearity of the converter is presented. These three topics are discussed below.

A. Step Response

For the step response analysis, a very severe situation was considered. Fig. 12 shows the simulation results for this analysis. In this simulation, the reactive current reference i_{q_ref} was changed from zero to -1 pu (inductive reference), then to $+1$ pu (capacitive reference) and back to zero. The simulated reactive current is very close to the reference, except during the time after the reference changes, when overshoot and undershoot appear.

The rise time of the reactive current is around 16 ms and the settling time is around 60 ms for the negative reference step and 100 ms for the positive reference step.

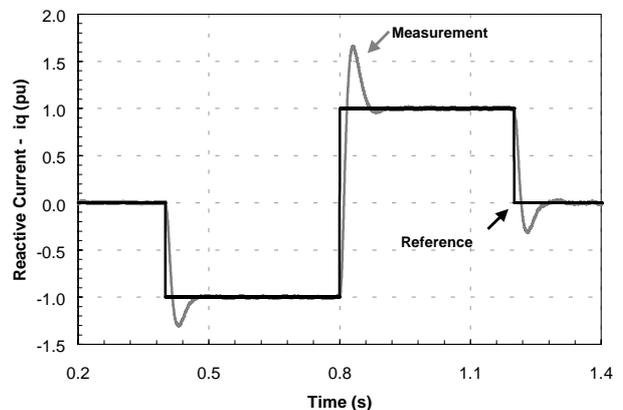


Fig. 12. Step response: reactive current

The overshoot, for the simulated conditions, is about 30% for the negative step and 70% for the positive step. These current overshoots occur during a very short time and can be easily managed by the STATCOM switches without overheating problem. This result clearly shows that there are nonlinearities in the STATCOM. However, as it will be shown later, this nonlinearity may be neglected.

Fig.13 shows the line voltage and the STATCOM current during the transition from 1 pu inductive to 1 pu capacitive compensation, which starts at $t = 0.8$ s. Initially, the converter current lags the line voltage. When the reactive current reference becomes capacitive, the converter current leads the line voltage, showing a very fast transition.

Fig. 14 shows that the STATCOM output voltage increases its value when the compensation changes from inductive to capacitive, as in a synchronous condenser. However, observe that the total transient time is much smaller than in a synchronous condenser.

B. Frequency Response

The frequency response analysis was done using also the EMT/ATP program. A sinusoidal signal was injected at the reactive current reference at various frequencies. For each frequency the output current magnitude and phase, converted to q coordinate, were measured. The Bode gain and phase diagrams were plotted and are depicted in Fig. 15. This figure shows that the analyzed twelve-pulse STATCOM has a flat frequency response up to 3 Hz, with

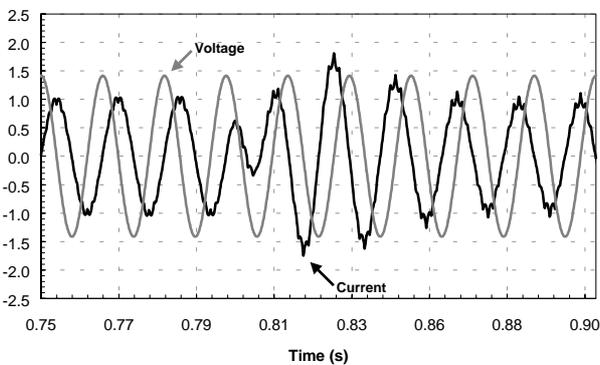


Fig. 13. Step response: line voltage and STATCOM current

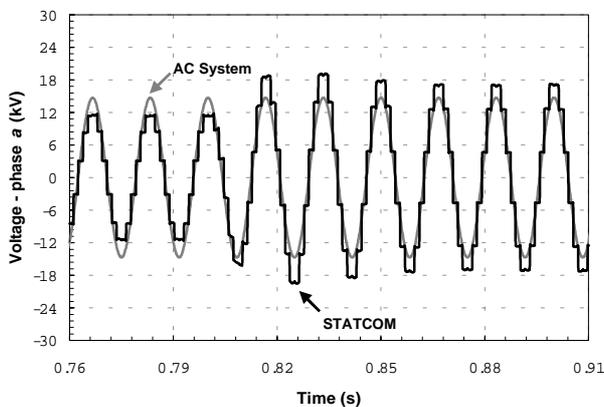


Fig. 14. Step response: voltage

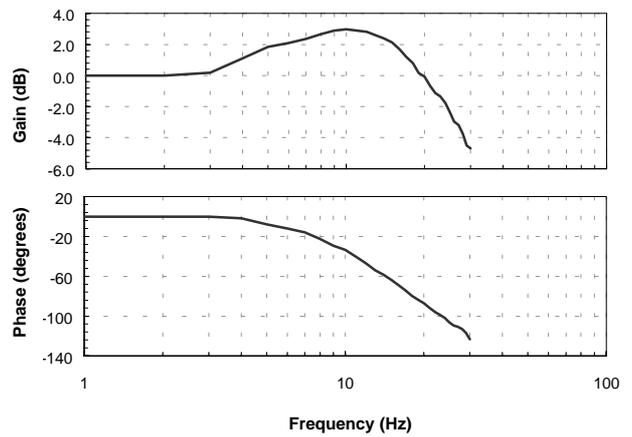


Fig. 15. Frequency response

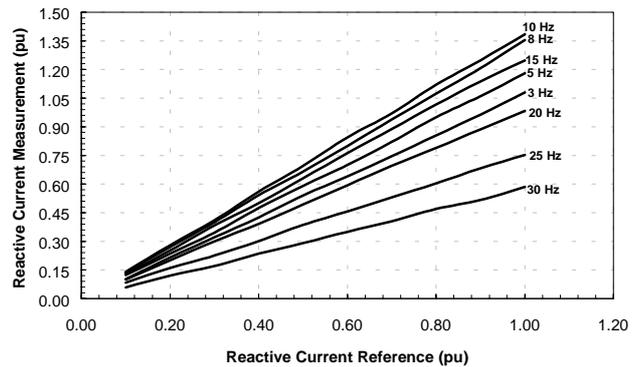


Fig. 16. Linearity analysis

a peak in 10 Hz and a bandwidth of approximately 20 Hz. If the STATCOM had a higher pulse number it would probably present a wider bandwidth.

The phase characteristic is flat up to 3 Hz, and therefore there is no delay in the STATCOM response up to this frequency. From 3 Hz up, this delay increases, reaching 90 degrees at 20 Hz.

This analysis is very important for the design of the STATCOM controller and to the authors knowledge this is an original result.

C. Linearity Analysis

One important property that should be checked is the linearity of the STATCOM. For this test, the reference current was made equal to a sinusoidal wave with amplitude varying from 0.1 to 1 pu. Thirty curves were obtained for frequencies varying from 1 to 30 Hz. A few of these curves are shown in Fig. 16. This figure shows that for each frequency there is a linear relationship between the reactive current measurement and the reference current.

It is interesting to observe that for each frequency the derivative is a constant. This constant increases with frequency in the range below 10 Hz. Above 10 Hz, it starts decreasing in accordance with the Bode diagram shown in Fig. 15.

This is a quite interesting result because, in general, the STATCOM is referred to as a nonlinear device because of its internal switching. However, when seen with a

macroscopic view, neglecting the harmonics components and considering only the fundamental component, it can be considered as a linear device.

V. THE CAPACITOR SIZE INFLUENCE

The DC capacitor has a strong influence on the STATCOM dynamic performance behavior. As shown in Fig. 14, to control the reactive power in a multi-pulse STATCOM, it is necessary to control the DC voltage. Therefore, when the STATCOM voltage is higher than the line voltage its current is capacitive, and when this voltage is smaller the current turns to be inductive. Charging or discharging the capacitor changes the STATCOM voltage and consequently controls the reactive power. To understand better the influence of the capacitor size in the charging or discharging process, can consider the following situation: Assume a hypothetical situation in which the time required to charge a given DC capacitor from one value of voltage to another is Δt ; if this capacitance is doubled this time would be doubled. Naturally, in this analysis it was assumed that the charging power of the VSC is the same in both cases. This facts shows that the size of the DC capacitor affects directly the dynamic performance of this type of STATCOM. In other words, we can say that by approximately doubling the capacitor size, the cut-off frequency will be halved. Or, using a smaller capacitor will provide a STATCOM with a faster dynamic response.

Studies and simulations are being executed to investigate the influence of the DC capacitor in other performance characteristics such as steady-state and dynamic (frequency and step response) behavior. These studies will prepare the background for better capacitor dimensioning.

VI. CONCLUSIONS

This paper presented a basic steady-state and dynamic analysis of a twelve-pulse STATCOM. Although this compensator has a low pulse number the harmonic analysis has shown that its current/voltage characteristics may be acceptable for some applications. In some cases a small passive filter may be necessary to eliminate the 11th and the 13th harmonic components in the current. Possibly, this type of STATCOM may find use in distribution systems.

The step response analysis has shown that the 12-pulse STATCOM has a much faster transient response than a conventional synchronous condenser.

The dynamic analysis has shown that the twelve-pulse STATCOM has a flat response up to 3 Hz and its bandwidth is around 20 Hz. The gain between the reactive current reference and the output current is basically linear, independently of the frequency.

It was shown that the connection of the STATCOM to an electric power system might cause resonance problems. Therefore, the total reactance between the converter and the line has to be carefully designed to avoid this problem.

The authors believe that this analysis be useful for the future design of STATCOM-based voltage or power factor control.

VII. REFERENCES

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VIII. ACKNOWLEDGEMENT

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