A Static Synchronous Compensator for Reactive Power Compensation
under Distorted Mains Voltage Conditions

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Abstract
In this paper a STATCOM system is presented applied for compensation of reactive power under distorted mains conditions. The developed STATCOM control system consists of two regulating loops - DC link voltage control loop with anti-windup PI controller and the current control loop with a feed-forward PI controller. The simulation results indicate that the developed control system performs well, ensuring displacement power factor compensation with good transient and steady state performance even under significantly distorted grid voltage conditions.

Keywords
STATCOM, reactive power compensation

Introduction
The improvement of electrical energy transmission efficiency has long been realized using passive power factor compensators containing shunt capacitors. Shunt capacitors are relatively inexpensive to install and maintain. Installing shunt capacitors in the load area or at the point where compensation is necessary increases the voltage stability. However, shunt capacitors have the problem of poor dynamics, poor voltage regulation and, beyond a certain level of compensation, a stable operating point is unattainable. Furthermore, the reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage; during low voltage conditions reactive power support drops, thus compounding the problem [1]. In addition, shunt capacitor compensators may suffer from resonances with distributed inductances of the utility grid.

Nevertheless, in practice shunt capacitors have proven to be sufficiently effective, provided that the line voltage is sinusoidal. However due to proliferation of different power electronic converters amongst industrial and household equipment, which often draw explicitly non-sinusoidal current, in some cases the grid voltage quality is affected considerably. This being the case, the application of passive capacitive power factor compensators becomes problematic, since capacitor’s reactance is decreased for higher voltage harmonic components leading to excessively increased capacitor currents. A typical industry solution for this problem is the application of tuned filter reactors in series with each compensation capacitor bank [2]. This solution, however, significantly increases the required capacitance and rated voltage of the capacitors, as well as the cost of the whole compensator. This justifies application of more advanced techniques like SCR based dynamic power factor compensators or STACOM converters, which can cope with all the problems mentioned above.

1. Static Synchronous Compensator (STATCOM)

STATCOM – Static Synchronous Compensator is a static synchronous generator operated as a parallel connection static reactive power compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage [3].

In addition to system voltage control, which typically is the main task of the STATCOM, it may also be employed for additional tasks such as damping of power system oscillations, which results in improvement of the transmission capability.

Fig. 1. Basic structure of STATCOM system

Structurally STATCOM is a voltage-source inverter (VSI) based device (Fig. 1.), which converts a DC input voltage into an AC output voltage in order to compensate the reactive power needs of the system. In case the system voltage drops sufficiently to force the STATCOM output to its ceiling, still its reactive power output is not affected by the grid voltage magnitude. Therefore, it exhibits constant current
characteristics when the voltage is low. STATCOM can provide instantaneous and continuously variable reactive power in response to grid voltage transients, enhancing the grid voltage stability. The STATCOM operates according to voltage source principles, which together with unique PWM (Pulsed Width Modulation) switching of power switches gives it unequalled performance in terms of effective rating and response speed [4]. This performance can be dedicated to active harmonic filtering [6] and voltage flicker mitigation, but it also allows providing reactive power compensation of the load.

2. Developed STATCOM Control System

According to the “p-q” theory the instantaneous power can be decomposed into three different instantaneous powers – instantaneous zero-sequence power \( p_0 \), instantaneous active power \( p \) and instantaneous reactive power \( q \) [5]. In case of three-phase three wire systems where no zero-sequence currents, can be present, the instantaneous power can be defined using Clark’s coordinate transformation in orthogonal \( \alpha \beta \) reference frame as follows:

\[
\begin{bmatrix}
p \\ q
\end{bmatrix} = \begin{bmatrix}
v_\alpha & v_\beta \\ v_\beta & -v_\alpha
\end{bmatrix} \begin{bmatrix}
i_\alpha \\ i_\beta
\end{bmatrix},
\]

(1)

where \( v_{\alpha\beta} \) and \( i_{\alpha\beta} \) are the voltage and current of the three phase system in Clark’s reference frame.

Considering that the Park’s transformation is power invariant and choosing a reference frame so that \( v_{\alpha\beta}=0 \), the active and reactive power of the load under consideration in Park’s reference frame can be given by:

\[
\begin{bmatrix}
p_l \\ q_l
\end{bmatrix} = v_{\alpha\beta} \begin{bmatrix}
i_\alpha \\ i_\beta
\end{bmatrix},
\]

(2)

where \( v_{\alpha\beta} \), \( i_{\alpha\beta} \) and \( i_{\alpha\beta} \) are the voltage and current in synchronous reference frame obtained by Park’s transformation (Fig. 2.).

\[
\begin{bmatrix}
v_{\alpha\beta} \\ i_{\alpha\beta}
\end{bmatrix} = D \begin{bmatrix}
\cos \theta & \sin \theta \\ -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
\cos \phi & -\sin \phi \\ \sin \phi & \cos \phi
\end{bmatrix} \begin{bmatrix}
v_{\alpha\beta} \\ i_{\alpha\beta}
\end{bmatrix}
\]

and

\[
\theta = \arctan \frac{v_{\alpha\beta}}{v_{\beta\alpha}}.
\]

(3)

Under non-sinusoidal and/or unbalanced conditions the equation (2) can be decomposed in average and oscillatory terms as follows:

\[
\begin{bmatrix}
p_l \\ q_l
\end{bmatrix} = \begin{bmatrix}
p_{l\alpha} + \bar{p}_{l\alpha} \\ q_{l\alpha} + \bar{q}_{l\alpha}
\end{bmatrix} = \begin{bmatrix}
\bar{v}_{\alpha\beta} + \bar{v}_{\alpha\beta} \\ \bar{v}_{\beta\alpha} + \bar{v}_{\beta\alpha}
\end{bmatrix} \begin{bmatrix}
i_{l\alpha} \\ i_{l\beta}
\end{bmatrix}
\]

(4)

where \( \bar{v}_{\alpha\beta} \) and \( \bar{v}_{\alpha\beta} \) are the average and the oscillatory terms of the power grid voltage and, \( \bar{i}_{l\alpha} \) and \( \bar{i}_{l\beta} \) are the average and the oscillatory terms of the load current.

Fig. 2. Load current and grid voltage phasors in Clark’s and Park’s reference frames

In accordance with the “p-q” theory, the instantaneous active power describes the energy flow in the system from source to load and its average value corresponds to active power in classical interpretation, while the average value of instantaneous reactive power corresponds to the reactive power in classical interpretation. The average terms of the grid voltage and load current represent the first harmonic components of positive sequence, but the oscillatory terms represent the harmonic voltages (currents) as well as the unbalanced condition of the grid.

Fig. 3: The block scheme of the control system
In order to compensate the displacement power factor of the load under consideration, the STATCOM converter must ensure the total average reactive power to be zero. Provided that the grid voltage is balanced and the harmonic distortion, if present, is eliminated in the grid voltage measurement signal, the compensation according to (4) can be achieved by generating compensation current along q axis, which is equal to the average load reactive current component \( i_{dq} \).

Figure 3 demonstrates the configuration of the developed STATCOM control system consisting of two regulating loops - control loop of the DC link voltage and control loop of the inverter's current. The task of the two control loops is to perform regulation of the VSI current as well as the DC link voltage \( v_{dc} \) in order to keep it constant and higher than the amplitude of the grid line voltage, if the inverter is to be able to generate the desired compensation current.

The DC link voltage control loop (Fig. 4.) compensates the active losses of the VSI and maintains a suitable level of the DC voltage. This loop contains an anti-windup PI regulator with the error of DC link voltage regulation at the input, but the output signal \( i_d \) is supplied to the current reference generator, where it contributes to the compensation current along d axis regulating the active power of the STATCOM.

\[
\begin{align*}
\text{Fig. 4. PI Controller for voltage loop} \\
&\text{The input of the reference generator, in accordance with the scheme given in Fig. 5, is the load current measurement signal } i_{abc}, \text{ and output signal of the DC link voltage control loop } i_d^*.
\end{align*}
\]

\[
\begin{align*}
\text{Fig. 5. Current reference generator} \\
\text{The reference current contains fundamental harmonic components in } dq \text{ axes for the control of the DC voltage and compensation of the displacement power factor of the load. The reference is found from the load current measurements filtering out the oscillating terms in the synchronous } dq \text{ reference frame with a LPF filter.}
\end{align*}
\]

The current regulator (Fig. 6) contains a second PI regulator with feed-forward of filtered grid voltage measurement in \( dq \) reference frame, which controls the current of the STATCOM according to the given reference, performing regulation of the fundamental component of the current reference in \( dq \) reference frame. The output is transferred to \( a\beta \) reference frame by inverse Park’s transformation.

\[
\begin{align*}
\text{Fig. 6. Current regulator for the current loop} \\
\text{The extraction of a correct current reference as well as the operation of the whole control system of the STATCOM converter is strongly dependant on a precise estimation of the phase of the fundamental positive sequence phasor } \theta \text{ of the grid voltage. The harmonic distortion, if present in the grid voltage, affects the whole current control loop, because the phase signal used for the Park’s reference frame transformations is distorted. A phase-locked-loop (PLL) system described in [7] is used here for a smooth estimation of the position of the grid voltage phasor containing simple software PLL applied to the fundamental component of the grid voltage measurement.}
\end{align*}
\]

3. Simulation Results of the STATCOM System

In order to investigate the developed STATCOM system a computer model in MATLAB/SIMULINK environment has been elaborated (Fig. 7). The control system described above is realized by means of C language embedded systems function, having several advantages – this approach allows applying the same control code for the simulation and experimental investigations using MATLAB RTI. Triggering of the control system is realized synchronously with PWM triangle-form carrier signal „Carrier”. At rising of interrupt signal „PWM_ISR” the control task is activated and the duty factors of the inverter’s legs are calculated to be applied in the succeeding period of PWM.

The power system model is shown in Fig. 8. The VSI of the STATCOM is connected in parallel with two identical active-inductive loads (\( P=10 \text{ kW}, Q=3 \text{ kvar} \) – one of the loads is enabled after a time delay of 500 ms (signal “full load” is activated) to simulate dynamic change in load power.

Simulation results in Fig. 9 illustrate the operation of the control system during the whole simulation time \( t = 0...0.8 \text{ s} \). At the instant \( t_1 = 50 \text{ ms} \) the soft start of the VSI DC-link capacitor is finished. At the instant \( t_2 = 60 \text{ ms} \) the execution of the control algorithm starts – the sequence of the supply voltage is detected and after two mains cycles PLL starts its operation, determining the phase of the supply voltage vector. After one more mains cycle the operation of PLL is stabilized and PWM control is actuated, which charges the DC-link up to the reference voltage \( (v_{dc} = 700 \text{ V}) \). At time instant \( t_3 = 300 \text{ ms} \) the compensation of the load reactive power is started.
Fig. 7: MATLAB/SIMULINK model of the STATCOM system

Fig. 8: MATLAB/SIMULINK model of the STATCOM power system

Fig. 9: Simulation results of the STATCOM system: DC-link voltage reference $v_{DC}^*$ and actual value $v_{DC}$; instantaneous phase angle $\theta$ of the grid voltage; active power $P$ (dashed) and reactive power $Q$ (solid) of phase $a$
The simulation results of active and reactive power of phase a of the STATCOM system (Fig. 9.), show that until around 100ms while the control of the STATCOM is not operational yet, the active power of one phase is around 3.3 kW and the reactive power 1 kvar in stationary state, but after the control system fully operates, DC link voltage increases till 700 V (reference voltage) and the reactive power is compensated approximately to zero. After 500 ms when the second load is enabled, the active power increases twice, but the reactive power is still kept to zero.

Figure 10 demonstrates the operation of the current regulator in steady-state mode – the regulation error hardly exceeds ±1 A even under distorted grid voltage (7% 5th and 5% 7th harmonic components are introduced in the grid voltage which results in THD of 8.5% as illustrated in Fig. 11.).

Conclusions

STATCOM system can be used for reactive power compensation in the industrial network grid and under distorted mains voltage conditions, it is more reliable than shunt capacitor reactive power compensator. Both the shunt capacitors and STATCOM increase the static voltage stability margin and power transfer capability, however STATCOM provides better performance in terms of dynamic load changes, grid voltage fluctuations and harmonic distortion. The STACOMs are relatively expensive, but taking into account that under distorted mains voltage conditions separate filter inductors have to be installed in series with each shunt capacitor battery, to ensure its rated current is not exceeded, the implementation of STATCOM systems is justified.

The simulation results of the developed STATCOM system presented in the paper indicate that the developed control system performs well – DC-link regulation is very smooth, current loop regulation error is relatively small too and the reactive power compensation has good transient and steady state performance. The results indicate, that developed STATCOM converter can provide robust load displacement power factor compensation even under significantly distorted (THD = 8.5%) grid voltage conditions.

References