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IMPROVING THE VOLTAGE STABILITY AS EXTREME LOAD VARIATIONS USING STATCOM

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ABSTRACT
The paper investigates the dynamic performance of the Static Synchronous Compensator (STATCOM) based on a decoupled current control strategy for combined reactive power compensation and voltage stabilization under various load conditions. A 24-pulse (three levels) Gate Turn-Off thyristor voltage source converter model is designed to represent the operation of the STATCOM within a power transmission system. The basic application of the STATCOM is to supply fast voltage support to the power system, therefore maximum response rate of the voltage regulation loop is always expected. This paper presents the novel method simulation for phase locked-loop for exact calculating converter firing angle using fast voltage measurement to improve STATCOM function and comprising it with other methods of simulation for phase locked-loop. The complete digital simulation of the STATCOM within the power system is performed in MATLAB/Simulink environment using the Power System Block set (PSB). The proposed novel phase locked-loop schemes for the STATCOM are fully validated by digital simulation.

KEY WORDS
STATCOM, voltage stability, reactive power compensation, decoupled current control, phase locked-loop, load variation.

1. Introduction

Shunt compensation is a well-known concept in ac power systems to control the reactive power flow and hence regulate the bus voltage. When the real power demand of the load increases, the amount of the required reactive power also increases and shunt compensation is required to provide this additional reactive power demand. At present, reactive power compensation can be classified into two main types, namely the static VAR compensator (SVC) and the Static Synchronous Compensator (STATCOM). STATCOM functions as a synchronous voltage source. It can provide reactive power compensation without the dependence on the ac system voltage. STATCOM can regulate the voltage at its location. Consequently, the voltage stability, transient stability, or load ability can be greatly improved if the voltage regulator can give fast and stable response. Three factors are found to have more influence on the voltage stability of the STATCOM, as follows: 1) the strength determines the amount of voltage varying due to a change in STATCOM reactive current output and hence directly influence stability of the STATCOM. If the impedance of the power system increases (weak system), the amount of voltage change due to the STATCOM reactive current increases and the overall system tends to instability. If the impedance of the power system decreases (strong system), the system is more stable, although the response is slower than that of the weak system. 2) The synchronizing signal is generated from zero-crossings of the bus voltage. In the case of a sudden change in the power system, such as load rejection, The pulse generator needs time nearly one period to modify the phase change of the fundamental positive sequence synchronizing signal and thus a time delay is introduced to the controller. If the STATCOM works with large reactive current output, the time delay will aggravate the voltage stability of the STATCOM. 3) The inherent dynamic response of the power system can lead to a time delay between STATCOM control action and change in ac voltage magnitude. Advance or delay firing angle with respect to phase voltage of the power system, will result in absorbing or generating of reactive power respectively. Gate Turn-Off thyristor voltage source converter are performed in high power system because of the commercial availability, high-power handling capability and the advancement of the other types of power-semiconductor devices such as IGBTs. Therefore, the paper investigates the reactive power control by STATCOM to improve voltage stability through regulating 24-pulse (three levels) firing angle, by the novel method of phase locked loop (PLL) simulation with the minimal time delay.[1] [2]

2. Static Synchronous Compensator

The STATCOM's main function is to regulate key bus voltage magnitude by dynamically absorbing or generating reactive power to the ac grid network, through the leakage reactance of the coupling transformer. The

STATCOM is, basically, composed of four basic parts seen in Fig. 1: inverters, transformers, dc capacitor and the control.

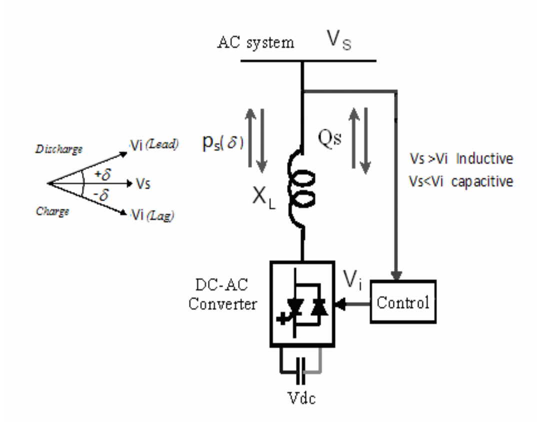

Figure 1. Static Synchronous Compensator

Whenever displacement angle between these two voltages is δ , the power relations are described by:

$$P_S = \frac{V_S V_i}{X_L} Sin\delta$$

$$Q_S = \frac{V_S^2 - V_S V_i}{X_L} Sin\delta$$

If the system voltage (V_S) and the STATCOM voltage (V_i) are synchronized, $\delta = 0$, there is only reactive power.

If $\delta = 0$, and $V_i < V_S$, the STATCOM behaves as an inductor, producing lagging currents and STATCOM consumes reactive power (Q_s) from the transmission system.

If $\delta = 0$, and $V_i > V_S$, the STATCOM behaves as a Capacitor, producing leading currents and STATCOM supplies reactive power (Q_s) in to the transmission system. To change the voltage amplitude of the STATCOM, small angle displacement, δ , is introduced, if V_i lags V_S , real power (p_s) flows from transmission system to dc side and the capacitor is charged. Similarly if V_i leads V_S , real power (p_s) flows from dc side to transmission system and the capacitor is discharged. The basic objective of a good voltage source-converter (VSC) is to produce a near sinusoidal ac voltage with minimal wave form distortion or excessive harmonic content.[3] Three basic techniques can be used for reducing the harmonics produced by the converter switching:

1) Harmonic neutralization using magnetic coupling (multipulse converter configurations), 2) harmonic reduction using multilevel converter configurations, 3) pulse-width modulation (PWM) switching techniques. Since pulse-width modulation (PWM) methods are limited to low and medium voltage power converter, therefore in this paper for investigating the exact STATCOM's function we have used the 24-pulse (three levels) voltage source converter with minimal wave form distortion and high power.

2.1 Complete digital simulation model of power system within STATCOM

Modeling the unified ac grid sample system with the STATCOM for the exact effect of phase locked loop's (PLL) simulation improving STATCOM's function, is shown in Fig. 2. The single line diagram represents the ±100 Mvar STATCOM device which is connected to the (230 KV-10000 MVA) through the coupling transformer. The full system parameters are given in appendix.

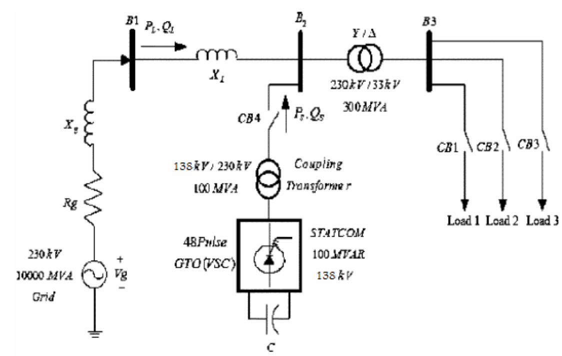

Figure 2. Single-line diagram of the simulated power system

Complete digital simulation model of quasi 24-pulse (three levels) STATCOM and simulation of decoupled current control system have been represented using two different methods of phase locked loop (PLL) simulation. The complete digital simulation of the STATCOM within the power system is performed in the MATLAB/ Simulink environment using the Power System block set (PSB).

2.2 24-pulse (three levels) voltage source converter

Two 12-pulse converters, phase shifted by 15 degrees from each other, can provide a 24-pulse converter. One approach for providing 15 degrees is to provide phase-shift windings for +7.5 degrees phase shift on the two transformers of one 12-pulse converter and -7.5 degrees on the two transformers of the other12-pulse converter. It is also necessary to shift the firing pulse of one 12-pulse converter by 15 degrees with respect to the other. 24-pulse converter, obviously has much lower harmonics on ac and dc side. Its ac output voltage would have 24n±1 order harmonics, i.e., 23^{rd} , 25^{th}, 47^{th}, 49^{th} ,…harmonics , with magnitudes of $1/23^{rd}$, $1/25^{th}$, $1/47^{th}$, $1/49^{th}$, … . Fig.3 depicts the schematic diagram of the 24-pulse VS-GTO converter model.

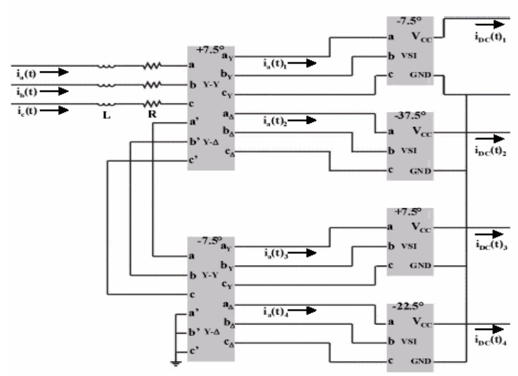

Figure 3. 24-pulse voltage source converter

If the output voltage of both converters are added, it results in a voltage closer to be a sine wave free of the 12-pulse harmonic components, that is, the 24-pulse voltage $v_{ab24}(t)$. Thus:

$$v_{ab24}(t) = v_{ab12}(t)_1 + v_{ab12}(t)_2$$

$$v_{ab24}(t) = 4\left[V_{ab_1} Sin(wt+30^\circ) + V_{ab23} Sin(23wt+150^\circ)\right.$$

$$\left. + V_{ab25} Sin(25wt+210^\circ) + V_{ab_{47}} Sin(47wt+330^\circ) + ...\right]$$

The general expression is given by,

$$v_{ab24}(t) = 4\sum_{n=1}^{\infty} v_{abn} Sin\ (nwt + 22.5^\circ n + 7.5^\circ i)$$

$$n = 24r \pm 1\ , \qquad r = 0,1,2,3$$

where: $i = 1$ for positive sequence harmonics, abc sequence

$i = -1$ for negative sequence harmonics, cba sequence

Fig. 4. Depicts the line- to- neutral voltage $v_{an24}(t)$.

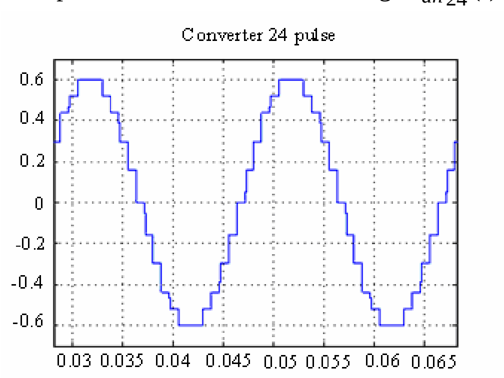

Figure 4. 24-pulse converter output voltage

Fig.5 . Shows the total harmonic distortion THD of the output voltage of converter which THD was measured to be 0.055. Therefore the generated 24-pulse voltage at the ac side of the converter can be considered almost a sinusoidal waveform.[3]

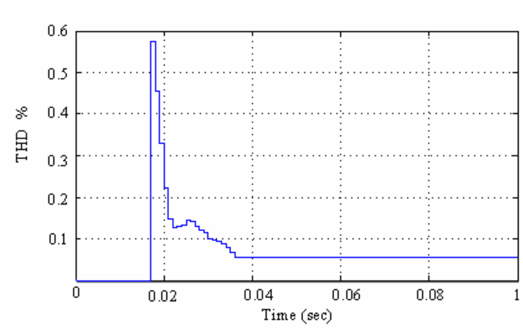

Figure 5. THD of the converter output voltage

2.3 Decoupled current control system

The decoupled current control system is based on a full d-q decoupled current control strategy using both direct and quadrature current components of the STATCOM ac current. The decoupled control system is implemented as shown in Fig. 6. A phase locked loop (PLL) synchronizes on the terminal voltage**.** The output of the PLL is the angle (θ) that is used to measure the direct axis and quadrature axis component of the ac three-phase voltage and current. The outer regulation loop compares terminal voltage (v_t) with the reference voltage (v_{ref}) and a proportional plus integral PI controller with k_p=.006 and k_i=3, provides the required reactive current of the STATCOM by considering the regulation-slope k=30.77 determines the compensation behaviour of the STATCOM device. To enhance the dynamic performance of the 24-pulse STATCOM device model, a supplementary regulator loop is added using the dc capacitor voltage.

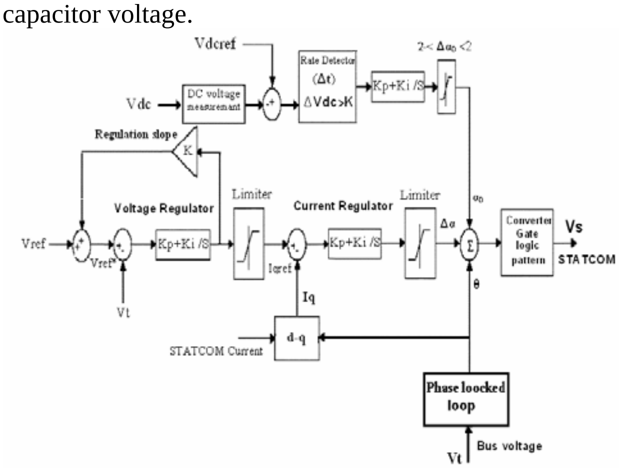

Figure 6**.** STATCOM d-q decoupled control system

Thus, for a fixed selected short time interval Δt, the variation in the V_{dc} magnitude is measured, and any rapid change in this dc voltage is measured and if $|\Delta V_{dc}|$ change is greater than a specified threshold k=0.05, the supplementary loop is activated. Now we investigate the effect of the phase locked loop (PLL) on dynamic stability of the power system, through the decoupled control system.[4] [5]

2.3.1 Phase-locked loop (PLL) simulation by the zero crossing of voltage method

The phase-locked loop (PLL) provides the synchronizing signal of the STATCOM which is the phase angle of the STATCOM bus voltage, θ. It is obtained from comparing the zero crossing of the STATCOM bus voltage with that of a reference voltage with zero phase angle. In the case of a sudden change in power system, such as adding or removing a load or system voltage variations, in addition to signal processing delay time it takes one period of voltage for the PLL to be synchronized with the new phase angle. During this time, the STATCOM operates at the previous phase angle while the bus voltage phase angle has already changed. Depending on the amount of a phase angle change, whether it is increased or decreased, an uncontrolled reactive power exchange occurs between the STATCOM and power system. Due to extreme load variations, the phase angle of the bus voltage can change greatly in one period, while the PLL is not synchronized with the bus voltage yet. This delay time in PLL may lead to more oscillations in voltage regulator.[5] So this kind of phase-locked loop can't defiantly ensure STATCOM's voltage stability function due to extreme load variations.

2.3.1.1 Digital simulation

To demonstrate the effect of the PLL delay by zero crossing voltage method, the system shown in Fig.2 was simulated. The simulation results for synchronizing signal (θ), bus voltage, STATCOM reactive power (Q) and STATCOM active power (P) are shown in Fig.7. The STATCOM is connected to the power system at t= 0.1 Sec with only load 1 in the system and the STATCOM is operating in capacitive mode and injects 0.69 pu of reactive power into the power system. the STATCOM draws 0.04 pu of real power from the grid to compensate switching and coupling transformer losses, as the result, the bus voltage is increases to 0.975 pu. At t= 0.4 Sec load 2 is switched in the power system, The STATCOM is supposed to inject more reactive power, but exactly at t=0.4 Sec, due to PLL inherent delay, the STATCOM voltage leads the bus voltage for about one a period and the real power flows from the dc capacitor to the transmission line and dc capacitor voltage drops sharply. Then the STATCOM compensates for the required power after the PLL delay and operates as expected and the bus voltage is decreased to 0.95 pu. At t=1 Sec, capacitive load is switched to the power system therefore the STATCOM injects less reactive power into the system.

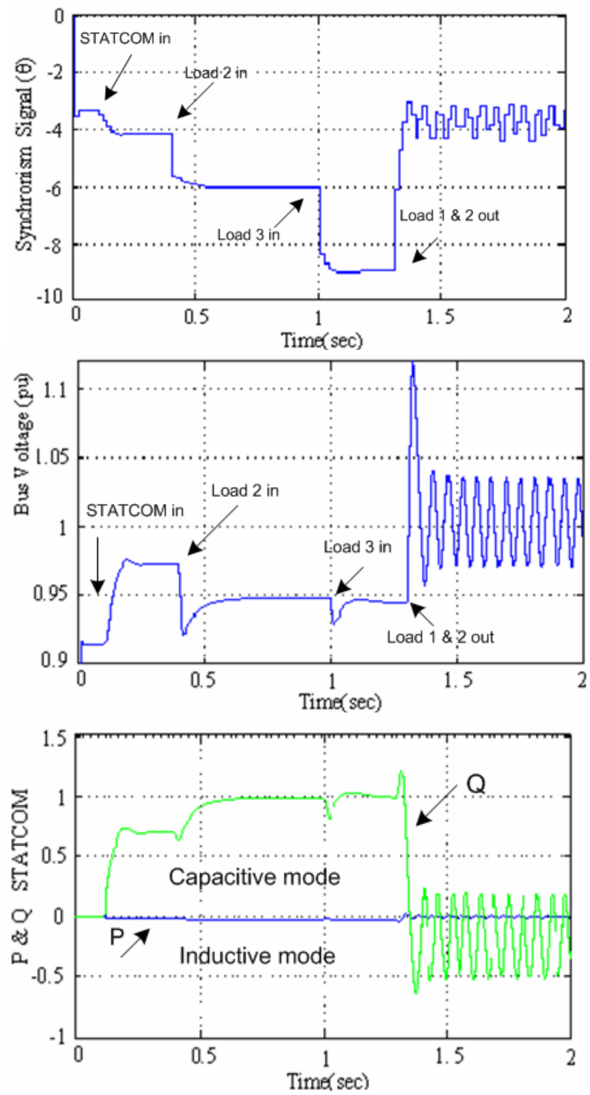

Figure 7. Digital simulation effect of the PLL delay on the STATCOM

At t=1.3 Sec, loads 1 and 2 are rejected and only load 3 remains connected. Exactly at t=1.3 Sec, PLL delay leads to uncontrolled oscillations in the function of simulated system because of extreme load variations and occurring great variations in phase angle.

2.3.2 Phase-locked loop (PLL) simulation by the space vector of voltage method

Measurement system and firing circuit are the most important parts of the STATCOM simulation. Reactive power generated by STATCOM, is controlled by the VSC firing angles. To simulate this control function, a phase-locked loop (PLL) is implemented on the digital simulation for creating the reference angle for firing circuit. To calculate the reference angle (θ_V), phase a, phase b and phase c of the system voltage can be represented by a space voltage vector v, as shown in Fig.8

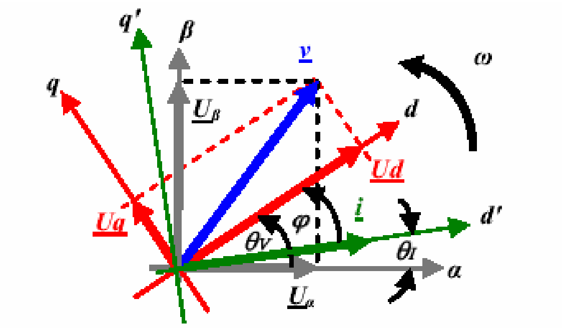

Figure 8. Vector diagram of voltage

The space vector v is transformed into the $\alpha\beta$ coordinate (stationary reference frame) by abc to $\alpha\beta$ transformation block. The results of the transformation are voltage U_α and U_β in $\alpha\beta$ coordinate. These voltages are used for calculating space vector Uq in the rotating reference frame. If phase angle of power system is locked with PLL, the space vector Uq is zero and Ud is equal to v. However, system phase angle may not be locked during a transient period and the space vector Uq is not zero.[5][6] The Uq becomes the positive value if the space vector v rotates faster than the rotation of dq axis. On the contrary, it becomes a negative value if the dq axis rotates faster than the rotation of space vector v. the pace vector Uq is inverted and then is fed to a PI controller. The fundamental frequency ($w_\circ$) is added to the output of the PI controller and then the result is integrated at 2π reset integrator block. The output of the integrator is the phase angle of space vector v. by doing so, the PLL will track system phase angle until the space vector Uq becomes zero. Consequently, system phase angle is locked and the reference phase angle (θ_V) represents the system phase angle. The reference phase angle (θ_V) is used as a feed back for control purposes by measuring fast bus voltage magnitude system.[7]

2.3.2.1 Digital simulation

The simulation results are shown in Fig.9. Only load 1 with P=1 pu and Q=0.8 pu, is in the system. The simulation steps are explained below:

a) t=0.1 Sec, STATCOM is switched to the power system. The STATCOM voltage lags the transmission line voltage by $\Delta\alpha = -1.2^\circ$ and therefore the dc capacitor voltage increases. The STATCOM is operating in capacitive mode and injects 0.55 pu of reactive power into the power system. As the result, the bus voltage increases to 0.975 pu.

b) t=0.4 Sec, inductive load 2 is switched to the power system. Since more reactive power compensation is required, the STATCOM phase displacement increases to $\Delta\alpha = -1.9^\circ$ and therefore the dc capacitor voltage increases.

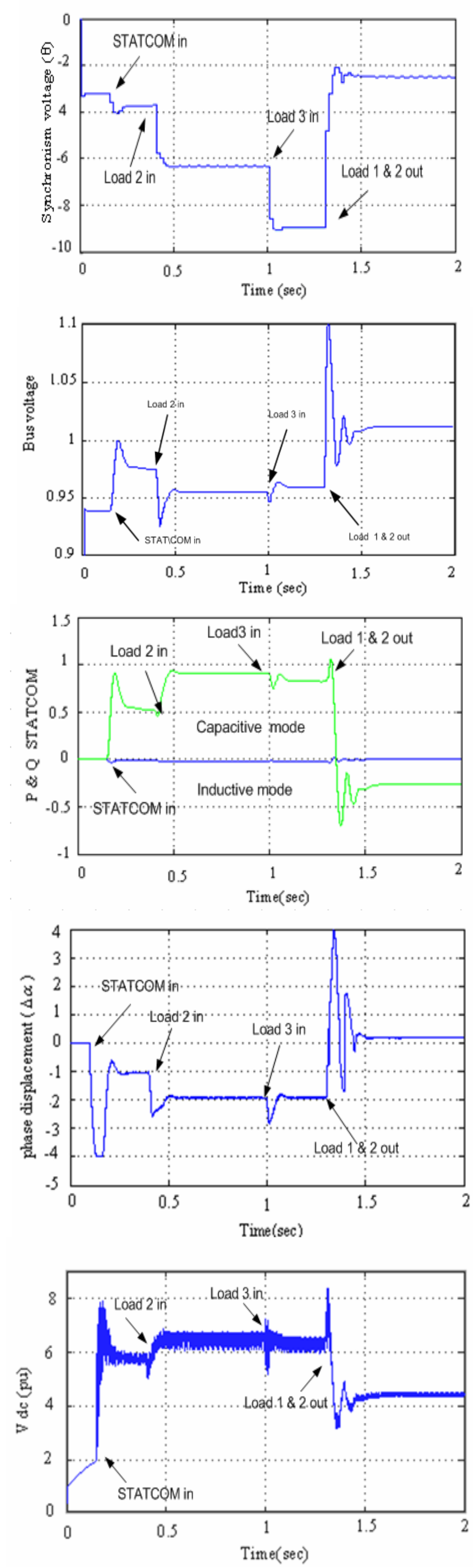

Figure 9. digital simulation results of the STATCOM

The STATCOM is operating in capacitive mode and injects 0.92 pu of reactive power into the power system. The regulated bus voltage is 0.955 pu. Exactly at t=0.4

Sec, the STATCOM is supposed to inject more reactive power, but due to sudden load variations, system phase angle may not be locked and advanced fire angle for STATCOM occurs in about some mili seconds, therefore the STATCOM dc capacitor is discharged as the real power flows from the STATCOM to the transmission line. As the result, there is a significant decrease of reactive power and bus voltage. So, STATCOM will exactly compensate network's reactive power by PLL tracking system phase angle in short time and calculates exact reference phase angle for firing circuit.

c) t=1 Sec, the capacitive load 3 is switched to the power system. Since the capacitive load has a compensative effect on the grid, the STATCOM injects less reactive power in to the system.

d) t= 1.3 Sec, load 1 and load 2 are rejected and only the capacitive load 3 remains in the power system. The STATCOM voltage leads the transmission line voltage by $\Delta\alpha = +0.2^{\circ}$ and therefore the dc capacitor voltage decreases. As the result, the bus voltage is 1.01 pu. Exactly at t=1.3 Sec, the STATCOM is supposed to draw more reactive power, but due to extreme sudden load variations, system phase angle may not be locked and delay fire angle for STATCOM occurs in about some mili seconds, therefore the STATCOM dc capacitor is charged as the real power flows from the transmission line to the STATCOM. As the result, there is a significant increase of reactive power and bus voltage. So, STATCOM will exactly compensate network's reactive power by PLL tracking system phase angle in a very short time and calculates exact reference phase angle for firing circuit.

3. Conclusion

In this paper we investigated the simulation of 24-pulse (three levels) Gate Turn-Off thyristor voltage source converter to provide exact model for STATCOM, and the effect on two kinds of phase locked-loop over voltage stability. Referring the simulation results, phase locked-loop with space vector method for measuring exact fire angle with the least delay effect and minimal wave form distortion, can ensure voltage stability function in result of extreme load variations.

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Appendix

The system parameters of Fig. 2 are:

There phase AC source:
Rated voltage: 230*1.03 KV
Frequency: 50 HZ
S.C Level: 10000 MVA
Base voltage: 230 KV
X/R= 8
Power transformer:
Nominal power: 300MVA
Prim. Voltage: 230 KV
Sec. Voltage: 33 KV
Resistance: 500
Reactance: 500
Three phase loads:
Load 1
Active power: 1 pu
Reactive power: 0.8 pu
Load 2
Active power: 0.7 pu
Reactive power: 0.5 pu
Load 3
Active power: 0.6 pu
Reactive power: 0.4 pu
STATCOM:
Nominal power: 100 MVAR
Prim. Voltage: 138 KV
Sec. Voltage: 15 KV
Eq. capacitance:750 μF
Coupling Transformer:
Nominal power: 100 MVA
Prim. Voltage: 138 KV
Sec. Voltage: 230 KV