A Control Method for Static VAR Compensator Based On Modular Multilevel Inverter

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Abstract-*Multilevel inverters are promised to provide a better performance in high power applications such as static VAR compensators. The proposed modular inverter has advantages compared to the conventional technologies. A control system of static VAR compensator using new modular multilevel inverter is proposed in this paper. Modeling and dynamic performance of static VAR compensator based on the proposed multilevel inverter are described in this paper. The inverter switching devices are switched at the fundamental output frequency. How to control the dc capacitor voltage is described. Several simulated results are included to verify the proposed concept.*

Keywords: Multilevel, inverter, STATCOM

I. INTRODUCTION

Reactive power compensation plays an important role in power systems. It minimize power transmission losses, maximize power transmission capability, and stabilize the power system[1]-[3]. The compensator using state-of-the-art technology of multilevel inverter had been widely accepted to replace the conventional ones. This kind of static VAR compensator is commonly called as STATCOM. It has been shown in the literature that this kind of static VAR compensator has better performance compared to the one that is based on thyristor technology [3]-[5].

There are various inverter topologies that can be used for static VAR compensators [6]-[14]. The most promising is the one that is based on multilevel inverter systems. By using multilevel techniques, better voltage sharing among the inverter switching devices can be achieved. Moreover, better output voltage waveform can be obtained without sacrificing the system efficiency. In high-power applications, PWM operation is prohibited because of switching losses problems.

The well proven topology that has been installed around the world is the one based on series connection of several three-phase inverters[6]-[12]. The inverter itself is operated under square-wave mode and, therefore, the switching losses are minimum. The inverter outputs are connected in series by using a special connected three-phase transformers to eliminate low-order harmonics. As the inverters are operated under square-wave mode, the only way to control the output voltage is by controlling the dc capacitor voltage. As the dc capacitance is large, a fast control response is difficult to achieve.

Another topology that has received a great interest in the recent years is the one based on cascaded inverters with separate dc sources [13]-[14]. In this topology, several single-phase full-bridge inverters are connected in series. This kind of inverter able to produce high output voltages without using transformer. The inverter is operated under quasi square-wave mode to control the output voltage. A fast response can be easily obtained as we don't need to control the dc capacitor voltage. The main problem of this STATCOM is controlling each dc capacitor voltage. Many voltage controllers must be installed with the associated complication. Moreover, the required modulation technique makes the utilization factors of each inverter are different.

In the companion paper[15], the authors have proposed a modular multilevel inverter that is suitable for high power applications. The proposed topology is also based on cascaded connection of several single-phase full-bridge inverters. In the proposed system, however, no special transformers are required. Conventional single-phase transformers are used. The proposed topology does not need separate dc sources and, therefore, no complicated dc voltage controllers are required. The use of transformer cannot be considered as a disadvantage because galvanic isolation is a must in high-voltage applications.

Static VAR Compensators (STATCOM) are connected in parallel to the system to control the reactive power. The challenge is to give a fast reactive power compensation with minimum losses and harmonics. Using the modular inverter design, it is possible to achieve those requirements. Fast reactive power can be achieved by controlling the output voltage by changing the gating signals of the inverters. Minimum harmonics are achieved by controlling the phase differences among the inverters.

Modeling and control techniques of the proposed modular multilevel inverter system that is operated as STATCOM are proposed in this paper. Park transformation is used to simplify the control and to eliminate the steady-state errors. A ten MVAR STATCOM is designed by using the proposed topology. Simulated results are included to show the feasibility of the proposed multilevel inverter system.

II. PROPOSED STATCOM

Fig. 1 shows the topology of the purposed STATCOM that is discussed in this paper. All single-phase inverter and transformer are identical and, therefore, can be considered as one module. A large dc electrolytic capacitor is connected in parallel on the dc side. IGCTs or IGBTs can be used as the switching devices. In practice, a small LCL filter is usually connected on the ac side to reduce high-order harmonics. In this paper, the effects of this LCL filter is neglected.

Each single-phase full-bridge inverter is operated under quasi square-wave mode as shown in Fig. 2. The rms value of the output voltage is controlled by controlling the β angle. It can be seen that the output voltage varies linearly to cosines of β/2. Instead of controlling the β, it is better to control the cosines of β/2. In order to reduce the low-order harmonics, the phase differences among the inverters must be selected appropriately. For N single-phase inverters in each phase, the phase difference is 60/N. By using N single-phase inverters, the order of harmonics will be

$$h = 6N \pm 1 \qquad (1)$$

By using N=5 as shown in Fig. 1, the minimum harmonic order is 29. Fig. 3 shows simulated output voltages of the proposed system.

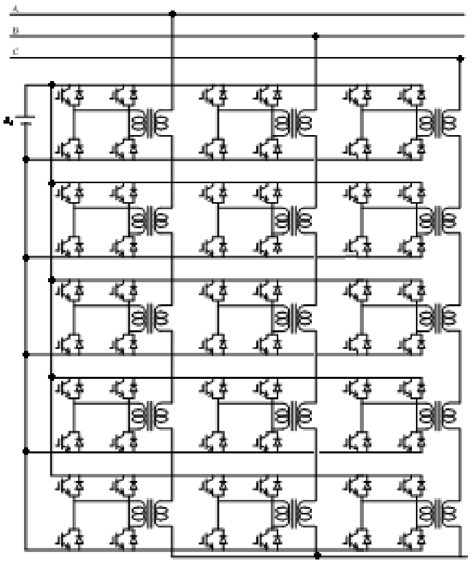
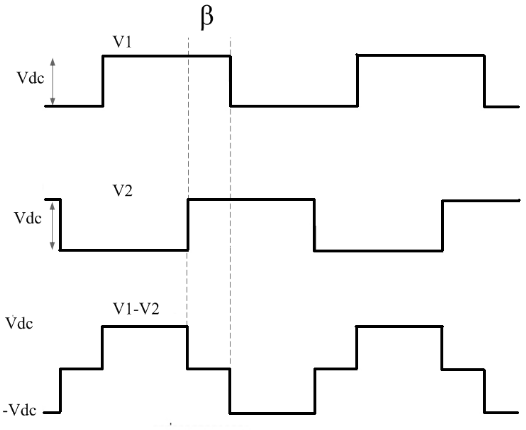


Fig.1. Proposed STATCOM system.



$$Vrms = \frac{4Vdc}{\sqrt{2}\pi} Cos(\frac{\beta}{2})$$

Fig. 2. Voltage control of full bridge inverter.

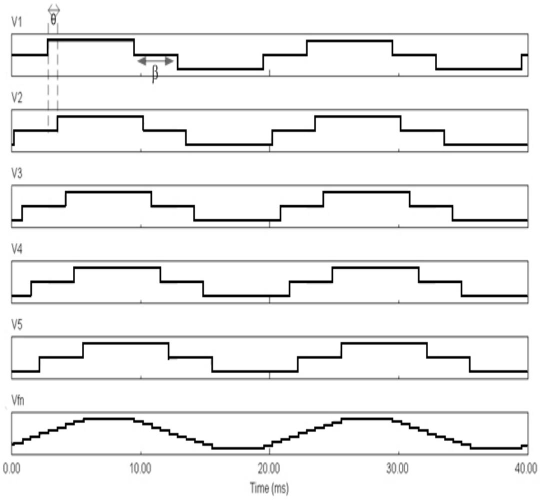


Fig. 3. STATCOM output voltages.

Based on inverter output voltages in Fig. 3, the inverter can be considered as an ideal voltage source. If the magnitude of inverter voltage is greater than the utility voltage then the STATCOM generates lagging reactive current, i.e. acting as a capacitor. On the other hand if the magnitude of inverter voltage is lower than the utility voltage then the STATCOM generates leading reactive current, i.e. acting as a reactor.

III. DYNAMIC ANALYSIS AND CONTROL

Many approaches have been developed for modeling STATCOM system [16]. The most common method is based on averaging theory. The utility and inverter phase peak voltages can be written as follows:

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{\sqrt{2}V_s}{\sqrt{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 2\pi/3) \\ \sin(\omega t + 2\pi/3) \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} = \frac{\sqrt{2}V_i}{\sqrt{3}} \begin{bmatrix} \sin(\omega t+\alpha) \\ \sin(\omega t+\alpha-2\pi/3) \\ \sin(\omega t+\alpha+2\pi/3) \end{bmatrix} \tag{3}$$

where is angle phase between power grid and inverter and ω is angular frequency of the power grid. In synchronous d-q frame, these voltages can be written as follows:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{so} \end{bmatrix} = [M].\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{4a}$$

and

$$\begin{bmatrix} V_{id} \\ V_{iq} \\ V_{io} \end{bmatrix} = [M]\begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} \tag{4b}$$

where [M] is:

$$\frac{\sqrt{2}}{\sqrt{3}} \begin{bmatrix} \cos(\omega t+\alpha) & \cos(\omega t+\alpha-2\pi/3) & \cos(\omega t+\alpha+2\pi/3) \\ \sin(\omega t+\alpha) & \sin(\omega t+\alpha-2\pi/3) & \sin(\omega t+\alpha+2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{5}$$

In synchronous *dq* reference frame, the output voltage expression is

$$L\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega L\begin{bmatrix} -I_d \\ I_q \end{bmatrix} + R\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} V_{sd}-V_{id} \\ V_{sq}-V_{iq} \end{bmatrix} \tag{6}$$

where

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} V_s \\ 0 \end{bmatrix} \tag{7}$$

and

$$\begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix} = \begin{bmatrix} V_i\sin\alpha \\ V_i\cos\alpha \end{bmatrix} \tag{8}$$

Based on the voltage expressions, the STATCOM can be represented by a block diagram as shown in Fig. 4. In STATCOM applications, the line resistance is usually very small and can be neglected. This block diagram shows that the d- and q-axis currents cannot be controlled independently.

Under synchronous reference frame, the instantaneous active and reactive powers can be written as follows:

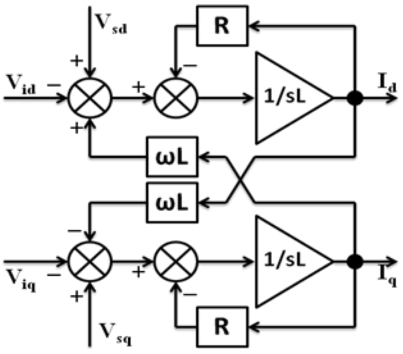


Fig. 4. STATCOM block diagram.

$$p = \frac{3}{2}V_{sd}I_d \tag{9}$$

$$q = \frac{3}{2}V_{sd}I_q \tag{10}$$

As the power grid is almost constant, we have to control the d- and q-axes currents to control the active and reactive power. The q-axis current is used to control the reactive power and the d-axis current is used to control the active power. Thus, a fast current controller is desirable in this application.

The complete block diagram of the proposed STATCOM controller is shown in Fig. 5. In this controller, we have two reference values, that are dc voltage and q-axis currents. The dc voltage reference value is compared to the actual value. The error is processed by a PI controller to generate the d-axis current reference. The actual d-axis and q-axis currents are compared to the reference values. The errors are processed by PI current controllers. Under synchronous reference frame, balanced and sinusoidal voltages and currents became dc quantities. Thus, PI current controllers result in zero steady-state errors.

To solve the coupling problem, a feedforward technique as shown in Fig. 5 is used. The actual output currents are multiplied by the line reactance to produce the additional signals to cancel the coupling effects. By using this method, the d-axis and q-axis currents can be controlled independently.

The output of the current controllers are the desired d-axis and q-axis inverter output voltages. By using a look up table, the required β and α angles are determined. For these purposes, the following expressions are used:

$$\beta = 2\left(\cos^{-1}\frac{\sqrt{3}/\sqrt{3}\,\sqrt{V_{id}^{*2}+V_{iq}^{*2}}}{K.V_{dc}}\right) \tag{11}$$

and

$$\alpha = \tan^{-1}\left(\frac{V_{iq}^{*}}{V_{id}^{*}}\right) \tag{12}$$

where K is a constant that refers to the characteristic of the topology, where $K = 7.$, and N is the turn ratio of the transformers. In the proposed topology, the value of K is 11.175.

The inverter output voltage must be synchronized to the power grid voltage. For this purpose, a phase locked loop circuit is used as shown in Fig. 5. Based on the information of β and θ angles, the gating signals for the inverter can be determined.

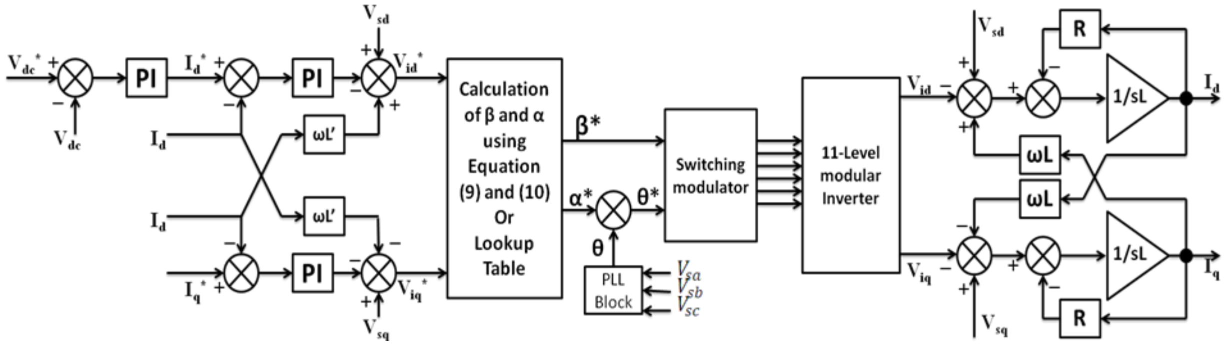


Fig. 5. Proposed controller.

IV. SIMULATION RESULTS

Computer software is used to simulate the proposed STATCOM. The system and STATCOM parameters are shown at Table 1. The STATCOM is rated at 10 MVAR and 20 kV. The dc voltage is maintained constant at 2100 Volt. By using this dc voltage, standard GTOs or IGCTs rated at 4.5 kV can be used. The dc side capacitance is 9.7 mF.

Fig. 6 and Fig. 7 show the response of the system when the q-axis current reference is suddenly changed to change the reactive power. The q-axis current is suddenly changed to produce zero MVAR to the rated 10 MVAR.

It can be seen that the reactive power can be produced according to the reference. Steady-state is reached in less than one cycle. The line currents are almost sinusoidal. In practice, an LCL filter is applied to reduce further high-order harmonic currents. The dc voltage is maintained constant during the change of condition. How to improve further the controller is under investigation.

Table 1. STATCOM parameters.

Source Voltage (Vs)	20 kV(rms) ± 5%
Var Rating (qs)	±10MVAR
DC voltage (Vdc)	± 2100 V
Total inductance (L)	10 mH
Total AC resistance (R)	0.27 Ω
Capacitance	9.7 mF

V. CONCLUSION

A controller for STATCOM based on modular multilevel inverter has been proposed in this paper. How to solve the coupling between d-axis and q-axis current controllers is proposed. Simulated result show that the overall system can achieve 1.2 ms response time when a step reference of 10 MVAR is applied. The dc voltage can be maintained constant under this condition. Further improvements of the proposed controller is under investigation.

REFRENCES

[1] L. Gyugyi, R. A. Otto, and T. H. Putman, Principles and Applications of Static Thyristor Controlled Shunt Compensators, *IEEE Trans. Power App. Sys*., Vol. 97, Sept./Oct. 1978, pp. 1935-1945.

[2] R. T. Byerly, D. T. Poznaniak, and E. R. Taylor, Static Reactive Compensation for Power Transmission Systems, *IEEE Trans. Power App. Sys*., Vol. 101, Oct. 1982, pp. 3997-4005.

[3] L. Gyugyi, Power Electronics in Electric Utilities: Static VAR Compensators, *Proc. IEEE*, Vol. 76, April 1988, pp. 483-494.

[4] E. Larsen, et.al., Benefits of GTO-Based Compensation Systems for Electric Utility Applications, *IEEE Trans. Power Del*., Vol. 7, Oct. 1992, pp. 2056-2064.

[5] A. E. Hammad, Comparing the Voltage Control Capabilities of Present and Future VAR Compensating Techniques in Transmission Systems, *IEEE Trans. Power Del*., Vol. 11, Jan. 1996, pp. 475-484.

[6] Y. Sumi, et.al., New Static VAR Compensator Using Force-Commutated Inverters, *IEEE Trans. Power App.* Sys., Vol. 100, Sept. 1981, pp. 4216-4224.

[7] C. W. Edward, et.al., Advanced Static VAR Generator Employing GTO Thyristors, *IEEE Trans. Power Del*., Vol. 3, Oct. 1988, pp. 1622-1627.

[8] L. H. Walker, 10-MW GTO Converter Battery Peaking Service, *IEEE Trans. Ind. Appl*., Vol. 26, Jan./Feb. 1990, pp. 63-72.

[9] S. Mori, et.al., Development of a Large Static VAR Generator Using Self-Commutated Inverters for Improving Power System Stability, *IEEE Trans. Power Sys*., Vol. 8, Feb. 1993, pp. 371-377.

[10] C. Schauder, et.al., Development of a ± 100 MVAR Static Condenser for Voltage Control of Transmission Systems, *IEEE Trans. Power Del*., Vol. 10, July 1995, pp. 1486-1496.

[11] H. Fujita, et.al., Analysis and Design of a DC Voltage-Controlled Static VAR Compensator Using Quad-Series Voltage-Source Inverters, *IEEE Trans. Ind. Appl*., Vol. 32, July/Aug. 1996, pp. 970-978.

[12] N. Seki and H. Uchino, Converter Configurations and Switching Frequency for a GTO Reactive Power Compensator, *IEEE Trans. Ind. Appl*., Vol. 33, July/Aug. 1997, pp. 1011-1018.

[13] F. Z. Peng and J. S. Lai, Dynamic Performance and Control of a Static VAR Generator Using Cascaded Multilevel Inverters, *IEEE Trans. Ind. Appl*., Vol. 33, May/June 1997, pp. 748-755.

[14] J. Dixon, et.al., Reactive Power Compensation Strategies: State of the Art Review, *Proc. IEEE*, Vol. 93, Dec. 2005, pp. 2144-2164.

[15] P. A. Dahono, H. N. Buwana, and R. Iswara, “A Modular Multilevel Inverter For High-Power Applications, *Ind. Electr. Sem*., Surabaya, 2*009*.

[16] P. Rao, et.al., STATCOM Control for Power System Voltage Control Applications, *IEEE Trans. Power Del*., Vol. 15, Oct. 2000, pp. 1311-1317.

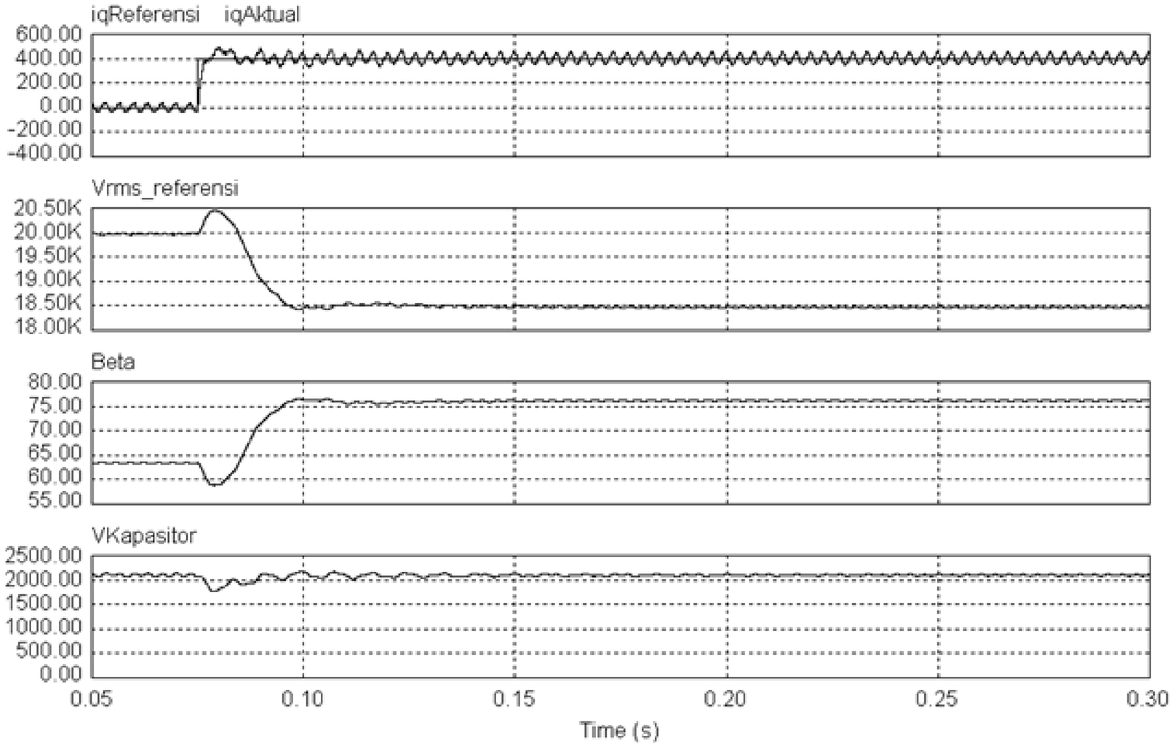


Fig. 6 Lagging operation.

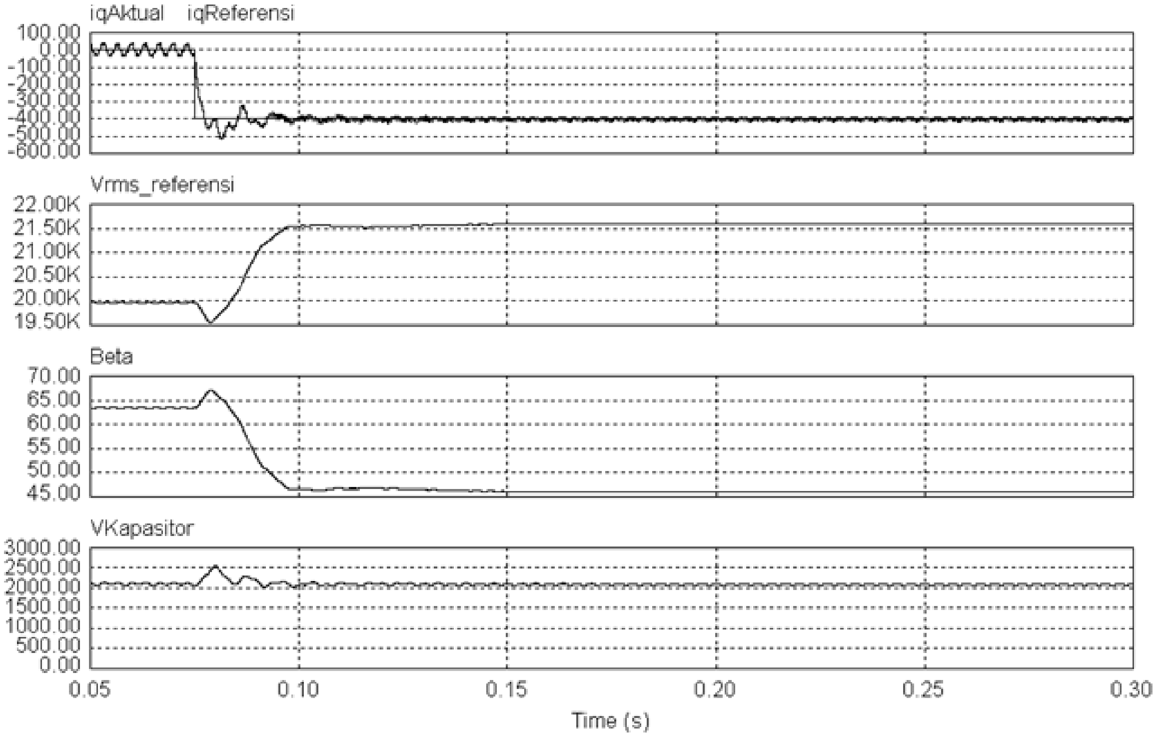


Fig. 7. Leading operation.