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Nonlinear DSTATCOM controller design for distribution network with distributed generation to enhance voltage stability

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ABSTRACT

This paper presents a nonlinear controller design for a DSTATCOM connected to a distribution network with distributed generation (DG) to regulate the line voltage by providing reactive power compensation. The controller is designed based on the partial feedback linearization which transforms the nonlinear system into a reduced-order linear system and an autonomous system whose dynamics are known as internal dynamics of the system. This paper also investigates the stability of internal dynamics of a DSTATCOM as it is a basic requirement to design partial feedback linearizing controllers. The performance of the proposed controller is evaluated in terms reactive power compensation to enhance the voltage stability of distribution with DG.

1. Introduction

The integration of small and medium size generation into distribution networks is increasing all over the world as these types of generating units offer a number of technical, environmental and economical benefits for utilities along with consumers due to their location near to customers [1–3]. The impact of integrating a single or small amount of distributed generation may not be a significant issue but the penetration of large fraction of distributed generation may become problematic and affects the voltage profile of low or medium voltage distribution networks [4–7].

The control of reactive power generation plays an important role to keep the voltage profile of distribution networks within the specified limits [8]. But distribution network service providers (DNSPs) require to operate DG at zero reactive power, i.e., unity power factor, or any other pre-defined power factor. For example, photovoltaic (PV) systems need to operate at unity power factor to extract maximum power [9]. Moreover, if a wind generator is connected to the distribution network as DG, it is essential to provide some reactive power to the system to maintain the voltage stability as its induction generator requires a source of reactive power to operate [10]. But if there is a combined heat power (CHP) unit within the system, it can provide reactive power to the system. However, the reactive power support provided by DG is not sufficient to maintain the predefined voltage profile of the distribution networks. Therefore, it is essential to provide, or absorb some reactive power to, or from distribution networks with DG.

Static compensators (STATCOMs), power electronic based shunt flexible AC transmission system (FACTS) devices are widely used to regulate the line voltage by providing appropriate reactive power support. When faults occur on a distribution network, sudden voltage sag will appear to that bus or adjacent buses and when DG connected to distribution networks consumes reactive power, the voltage dip occurs within the system. In this case, STATCOMs are used as a source of reactive power generation. But when DG connected to distribution networks exports reactive power, the voltage rise may occur within the system and STATCOMs can be used as a reactive power absorber. STATCOMs connected to distribution networks are known distribution or distributed STATCOMs (DSTATCOMs). To regulate the line voltage, it is essential to design an appropriate controller for STATCOMs or DSTATCOMs.

DSTATCOMs are used in [11] to compensate the voltage sag induced by loads. In [11], a PI controller is designed to regulate the voltage for a linear DSTATCOM model. A deadbeat control algorithm is applied to a DSTATCOM in [12] to regulate the line voltage by maintaining power balance at the point of common coupling (PCC) through the regulation of DC capacitor voltage. An energy-based fast-acting linear dc-link voltage controller is suggested [13] to ensure the fast transient response of the compensator.

DSTATCOMs exhibit nonlinear behaviors where nonlinearities occur due to stochastic behavior of the point of common coupling (PCC) voltage and nonlinear switching functions of inverters [14,15]. Linear controllers for nonlinear DSTATCOMs as presented

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in [11–15], provide satisfactory operation over a fixed set of operating points as the system is linearized at an equilibrium point. The restrictions of operating points can be solved by implementing nonlinear controllers for nonlinear DSTATCOM models.

Feedback linearization is a straightforward way to design nonlinear controllers as it transforms a nonlinear system into a fully linear or partly linear system by canceling the inherent nonlinearities within the system and linear controller design techniques can be employed to design the controller for the linearized system [16,17]. When feedback linearization transforms a nonlinear system into a fully linear system, the approach is called exact feedback linearization and if the system is transformed into partially linearized system, the approach is known as partial feedback linearization [16]. Since feedback linearization cancels nonlinearities by introducing nonlinear terms, the feedback linearized system is independent of operating points. The exact linearization approach is widely used as STATCOM controllers to regulate the voltage of transmission network as well as distribution networks [18–20]. But DSTATCOMs can be partially linearized rather than fully linearized and in this case, exact linearization is no more applicable.

The main focus of this paper is to design a partial feedback linearizing controller which is able to control both the dc-link voltage and the reactive current of DSTATCOMs. Partial feedback linearization not only transforms the nonlinear system into a reduced-order linear system but also an autonomous system whose dynamics are known as internal dynamics. The stability of these internal dynamics needs to be ensured before implementing partial feedback linearizing controller. This paper also addresses the issue related to the stability of internal dynamics of DSTATCOMs. The performance of the proposed controller is investigated on a distribution network which has PV and CHP generators as distributed generation.

2. DSTATCOM model

The structure of a six-pulse DSTATCOM connected to an AC distribution system is shown in Fig. 1 where DSTATCOM is connected through a filter and transformer. The capacitor within the DSTATCOM is used as an energy storage device. In order to establish a useful mathematical model, the following assumptions are considered [21]:

- Distribution networks are considered as three-phase balanced networks.
- All losses within the DSTATCOM are represented by equivalent resistances, and transformers and filters are represented as equivalent inductances.
- The inverter is considered as an ideal sine wave generator and only the fundamental-frequency components and aperiodic components are taken into account.

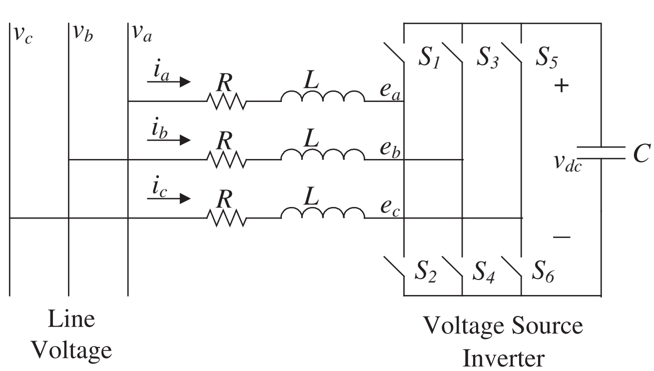

Fig. 1. DSTATCOM connected to distribution system.

Now by applying electrical relationship in Fig. 1 circuit differential equations can be written as follows:

$$\begin{aligned} \dot{i}_a &= -\frac{R}{L} i_a + \frac{1}{L}(v_a - e_a) \\ \dot{i}_b &= -\frac{R}{L} i_b + \frac{1}{L}(v_b - e_b) \\ \dot{i}_c &= -\frac{R}{L} i_c + \frac{1}{L}(v_c - e_c) \end{aligned} \tag{1}$$

where R represents the inverter and transformer conduction losses; L represents the equivalent inductance of transformer and filter; i_a, i_b, and i_c are AC currents of DSTATCOM; v_a, v_b, and v_c are line voltages; and e_a, e_b, and e_c are the inverter output voltage.

Since the system is considered as a three-phase balanced system, it can be transformed into a synchronously rotating dq frame. If the angular velocity of the AC voltage and current vectors is ω and it is considered that the system of reference dq is rotating in the same speed and θ is the angle between the d-axis and line voltage vector, then Eq. (1) can be transformed into the following dq frame:

$$\begin{aligned} \dot{I}_d &= -\frac{R}{L} I_d + \omega I_q + \frac{1}{L}(V_d - E_d) \\ \dot{I}_q &= -\omega I_d - \frac{R}{L} I_q + \frac{1}{L}(V_q - E_q) \end{aligned} \tag{2}$$

As a pulse width modulation (PWM) technique is used in the DSTATCOM and harmonics produced by the inverter are neglected, the equations relating AC- and DC-side can be written as

$$\begin{aligned} E_d &= M v_{dc} \sin\alpha \\ E_q &= M v_{dc} \cos\alpha \end{aligned} \tag{3}$$

where v_{dc} is the voltage across the capacitor C_{dc}, M is modulation index, and α is the firing angle. This M and α are the control variables of the DSTATCOM which can be written as

$$\begin{aligned} M &= \frac{\sqrt{E_d^2 + E_q^2}}{v_{dc}} \\ \alpha &= \arctan\left(\frac{E_q}{E_d}\right) \end{aligned} \tag{4}$$

The power equations can be written as

$$\begin{aligned} P &= \frac{3}{2}(V_d I_d + V_q I_q) \\ Q &= \frac{3}{2}(V_d I_q - V_q I_d) \end{aligned} \tag{5}$$

where P is real power and Q is reactive power. The power balance equation for inverter can be written as

$$P = v_{dc} C_{dc} \frac{d v_{dc}}{dt} \tag{6}$$

Eq. (6) can be simplified as

$$\dot{v}_{dc} = \frac{1}{C}(M\cos\alpha I_d + M\sin\alpha I_q) \tag{7}$$

where $C = \frac{3}{2} C_{dc}$. Eqs. (2) and (7) represent mathematical model of a DSTATCOM and therefore, these two equations can be written together as follows:

$$\begin{aligned} \dot{I}_d &= -\frac{R}{L} I_d + \omega I_q + \frac{1}{L}(V_d - M v_{dc}\cos\alpha) \\ \dot{I}_q &= -\omega I_d - \frac{R}{L} I_q + \frac{1}{L}(V_q - M v_{dc}\sin\alpha) \\ \dot{v}_{dc} &= \frac{1}{C}(M\cos\alpha I_d + M\sin\alpha I_q) \end{aligned} \tag{8}$$

Eq. (8) is the complete mathematical model of a DSTATCOM which is nonlinear due to the switching functions. Now, if θ is chosen as zero, then

$$V_q = 0, \quad \text{and} \quad Q = \frac{3}{2} V_d I_q \tag{9}$$

Therefore, it is sufficient to control the current I_q to control reactive power Q and in order to compensate reactive power Q, it is also essential to regulate the DC voltage v_{dc}.

3. Feedback linearization and partial feedback linearizability of DSTATCOM

The mathematical model of a DSTATCOM can be expressed a multi-input multi-output (MIMO) nonlinear system as follows:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2 \\ y_1 &= h_1(x) \\ y_2 &= h_2(x) \end{aligned} \tag{10}$$

where

$$x = [I_d \quad I_q \quad v_{dc}]^T$$

$$f(x) = \begin{bmatrix} -\frac{R}{L} I_d + \omega I_q + \frac{V_d}{L} \\ -\omega I_d - \frac{R}{L} I_q \\ 0 \end{bmatrix}$$

$$g(x) = \begin{bmatrix} -\frac{v_{dc}}{L} & 0 \\ 0 & -\frac{v_{dc}}{L} \\ \frac{I_d}{C} & \frac{I_q}{C} \end{bmatrix}$$

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \left[\begin{bmatrix} M\cos\alpha \\ M\sin\alpha \end{bmatrix} \right]$$

and

$$4 \cdot y = [I_q \quad v_{dc}]^T$$

The nonlinear system in (10) can be often linearized using feedback linearization [22]. Consider the following nonlinear coordinate transformation.

$$z = [h_1 \quad L_f h_1 \quad \cdots \quad L_f^{r_1-1} h_1 \quad h_2 \quad L_f h_2 \quad \cdots \quad L_f^{r_2-1} h_2]^T \tag{11}$$

where $r_1 < n$ and $r_2 < n$ are integers, $L_f h_i(x) f(x) = \frac{\partial h_i}{\partial x} f(x)$, $i = 1, 2$ are the Lie derivative of $h_i(x)$ along $f(x)$ [16]. This transforms the nonlinear system (10) with the state vector x into a linear dynamic system with the state vector z provided that the following conditions are satisfied for $n = r_1 + r_2$:

$$\begin{aligned} L_{g_1} L_f^k h_i(x) &= 0 \\ L_{g_2} L_f^k h_i(x) &= 0 \end{aligned} \tag{12}$$

where $i = 1, 2$; $k < r_i - 1$ and

$$\begin{aligned} L_{g_1} L_f^{r_i-1} h_i(x) &\neq 0 \\ L_{g_2} L_f^{r_i-1} h_i(x) &\neq 0 \end{aligned} \tag{13}$$

where $L_g L_f h_i(x)$ is the Lie derivative of $L_f h_i(x)$ along $g(x)$. Integers r_1 and r_2 are known as the relative degree of the system corresponding to the output function $h_1(x)$ and $h_2(x)$, respectively [15]. If these conditions are satisfied, a linear controller can be design for the linearized system

$$\dot{z} = Az + Bv \tag{14}$$

where A is the system matrix for the feedback linearized system, B is the input matrix for the feedback linearized system, and v is the new control input for the feedback linearized system.

When $r_1 + r_2 < n$, we can do only partial linearization and this case, the transformed states z can be written as

$$z = \phi(x) = [\tilde{z} \quad \hat{z}]^T$$

where $\tilde{z}$ represents the states obtained from the nonlinear coordinate transformation up to the order $r_1 + r_2$ and $\hat{z}$ represents the states related to the remaining $n - r_1 + r_2$ order. The dynamics of $\hat{z}$ is called the internal dynamics and its stability needs to be ensured before designing the linear controller for the following partially linearized system

$$\dot{\tilde{z}} = \widetilde{A}\tilde{z} + \widetilde{B}\tilde{v} \tag{16}$$

where $\widetilde{A}$ is the system matrix for the partially linearized system, $\widetilde{B}$ is the input matrix for the partially linearized system, and $\tilde{v}$ is the new control input for the partially linearized system.

The partial linearizability of the DSTATCOM represented by Eq. (10) can be obtained by calculating the relative degree corresponding to the output functions. The relative degree corresponding to $h_1(x) = I_q$ can be calculated as

$$L_g h_1(x) = L_g L_f^{1-1} h_1(x) = -\frac{v_{dc}}{L} \neq 0 \tag{17}$$

where $r_1 = 1$. Similarly, the relative degree corresponding to $h_2(x) = v_{dc}$ can be calculated as follows:

$$L_g h_2(x) = \frac{1}{C}(I_d + I_q) \neq 0 \tag{18}$$

which indicates $r_2 = 1$. Therefore, $r_1 + r_2 = 2$ which means that $r_1 + r_2 < n$ as $n = 3$. Therefore, the system is partially linearized for the chosen output functions. To implement partial feedback linearizing control for this system, the internal dynamics of the system need to stable. The controller design process is covered in the following section.

4. Controller design

This section presents the essential steps to design a partial feedback linearizing controller for the DSTATCOM.

4.1. Nonlinear coordinate transformation and partial linearization

A nonlinear coordinate transformation can be written as:

$$\tilde{z} = \tilde{\phi}(x) \tag{19}$$

where $\tilde{\phi}$ is the function of $ × $. For a DSTATCOM, we choose

$$\tilde{z}_1 = \tilde{\phi}_1(x) = h_1(x) = I_q \tag{20}$$

and

$$\tilde{z}_2 = \tilde{\phi}_2(x) = h_2(x) = v_{dc} \tag{21}$$

Using the above transformation, the partially linearized system can be obtained as follows:

$$\begin{aligned} \dot{\tilde{z}}_1 &= \frac{\partial h_1}{\partial x}\dot{x} = L_f h_1 + L_{g_1} h_1 u_1 + L_{g_2} h_1 u_2 \\ \dot{\tilde{z}}_2 &= \frac{\partial h_2}{\partial x}\dot{x} = L_f h_2 + L_{g_1} h_2 u_1 + L_{g_2} h_2 u_2 \end{aligned} \tag{22}$$

For the DSTATCOM as represented by Eq. (10)

$$\begin{aligned} \dot{\tilde{z}}_1 &= -\omega I_d - \frac{R}{L} I_q - \frac{v_{dc}}{L} u_2 \\ \dot{\tilde{z}}_2 &= \frac{1}{C} I_d u_1 + \frac{1}{C} I_q u_2 \end{aligned} \tag{23}$$

The above system can be written as the following linearized form:

$$\dot{\tilde{z}}_1 = v_1 \qquad \dot{\tilde{z}}_2 = v_2 \tag{24}$$

where v_1 and v_2 are the linear control inputs expressed as

$$v_1 = -\omega I_d - \frac{R}{L}I_q - \frac{v_{dc}}{L}u_2 \qquad v_2 = \frac{1}{C}I_d u_1 + \frac{1}{C}I_q u_2 \tag{25}$$

which can be obtained by using a linear control technique for the system (24). But before designing and implementing controller through partial feedback linearization, it is essential to check the stability of internal dynamics which is presented in the next step.

4.2. Stability of internal dynamics of the DSTATCOM

In the previous step, a third-order DSTATCOM is transformed into a second-order system which represents the external dynamics of the system. The good performance of the external dynamics can be obtained through a controller. The control law needs to be chosen in such a way that

$$\lim_{t\to\infty} h_i(x) \to 0$$

which implies $[\tilde{z}_1 \quad \tilde{z}_2 \quad \cdots \quad \tilde{z}_r]$ [15]. For the DSTATCOM considered in this work, this means that $\tilde{z}_1 = \tilde{z}_2 = 0$ which indicates

$$\dot{\tilde{z}}_1 = 0 \qquad \dot{\tilde{z}}_2 = 0 \tag{26}$$

Let the remaining state be $\hat{z}_3 = \hat{\phi}(x)$. This needs to be selected in such a way that it must satisfy the following conditions [21]:

$$L_{g_1}\hat{\phi}(x) = 0 \qquad L_{g_2}\hat{\phi}(x) = 0 \tag{27}$$

For a DSTATCOM, Eq. (27) will be satisfied if we chose

$$\hat{\phi}(x) = \hat{z}_3 = \frac{1}{2}LI_d^2 + \frac{1}{2}LI_q^2 + \frac{1}{2}Cv_{dc}^2 \tag{28}$$

By using $\tilde{z}_1 = I_q$ and $\tilde{z}_2 = v_{dc}$, Eq. (28) can be written as:

$$I_d^2 = \frac{2}{L}\hat{z}_3 - \tilde{z}_1^2 - \frac{C}{L}\tilde{z}_2^2 \tag{29}$$

Thus, the remaining dynamics of the system can be obtained as follows:

$$\dot{\hat{z}} = L_f\hat{\phi}(x) = LI_d f_1 + L\tilde{z}_1 f_2 + C\tilde{z}_2 f_3 \tag{30}$$

After performing some manipulations and using $\tilde{z}_1 = I_q = 0$ and $\tilde{z}_2 = v_{dc} = 0$ Eq. (30) can be simplified as

$$\dot{\hat{z}}_3 = -\frac{2R}{L}\hat{z}_3 \tag{31}$$

Eq. (31) represents the stable internal dynamics of the DSTATCOM. Therefore, partial feedback linearization can be used for the considered DSTATCOM. It is clear that partial feedback linearization divides the dynamics of a nonlinear system into two parts: one is the external dynamics as described in the previous step; and the other is the system with internal dynamics. The derivation of the proposed control law is shown in the following step.

4.3. Derivation of control law

From Eq. (25), the control law can be obtained as follows:

$$u_2 = \frac{L}{v_{dc}}\left(v_1 + \omega I_d + \frac{R}{L}I_q\right) \qquad u_1 = -\frac{C}{I_d}\left[v_2 - \frac{LI_q}{Cv_{dc}}\left(v_1 + \omega I_d + \frac{R}{L}I_q\right)\right] \tag{32}$$

Eq. (32) is the final control law for the DSTATCOM. At this point, the only thing which needs to be designed is the new linear control input v_1 and v_2. In this paper, PI controllers are used to track the reference outputs I_{qref} and v_{dcref}. The following two PI controllers are considered to track the output,

$$v_1 = k_{1p}(I_{qref} - I_q) + k_{1i}\int_0^t (I_{qref} - I_q)dt \qquad v_2 = k_{2p}(v_{pvref} - v_{pv}) + k_{2i}\int_0^t (v_{pvref} - v_{pv})dt \tag{33}$$

The gains need to be selected in such a way that the output follows the reference current to minimize the error. In this paper, the gains are set as follows:

$$k_{1p} = 2I_{qref}, \; k_{1i} = I_{qref}^2$$

and

$$k_{2p} = 2v_{dcref}, \; k_{2i} = v_{dcref}^2$$

In this case, the gains of the PI controllers depend on the reference values of the voltage and current. These reference values are calculated from estimated reactive power. The way of reactive power estimation can be seen in [23]. If the estimated reactive power is considered as reference power Q_{ref} to improve the voltage profile of distribution networks, the reference current can be calculated as

$$I_{qref} = \frac{2}{3}\frac{Q_{ref}}{E_d} \tag{34}$$

Using this current reference, the DC voltage reference v_{dcref} can be obtained as [24],

$$v_{dcref} = V_d + RI_{qref} + \omega LI_{qref} \tag{35}$$

The performance of the proposed controller on a DSTATCOM connected to distribution network with DG is evaluated in the following section.

5. Simulation results

The performance of the proposed controller is evaluated on a 12-bus three-phase balance distribution system [25] as shown in Fig. 2. The test system presented in [25] in modified by the wind generator to a PV generator and at bus 12, the capacity of DSTATCOM is considered as 2 Mvar. In Fig. 2, bus-4 is the PCC and under normal operating condition, distributed PV and CHP generators supply the load connected to bus-9 and bus-11 and the access power is supplied to the main distribution system (DS). At this point, the reactive power demand of the load is met by the CHP-based synchronous generator.

When a fault occurs within the system, the transfer of energy from DG to the infinite bus is considerably hampered and the voltage profile of the system is affected. Moreover, if the fault persists for a long time, the system undergoes to the voltage instability. In this situation, it is essential maintain the specified voltage profile of PCC for the stable operation of the distribution network and this can be performed absorbing energy from the system and releasing energy to the system through the DSTATCOM at the appropriate time when required. The proposed controller applied to the DSTATCOM is able to do these tasks efficiently.

To investigate the performance of the proposed controller, a three-phase fault is applied at bus-2 at $t = 1$ s and the fault is

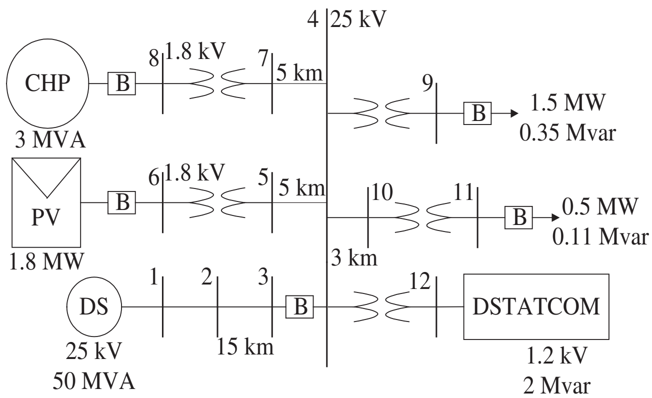

Fig. 2. Test distribution system.

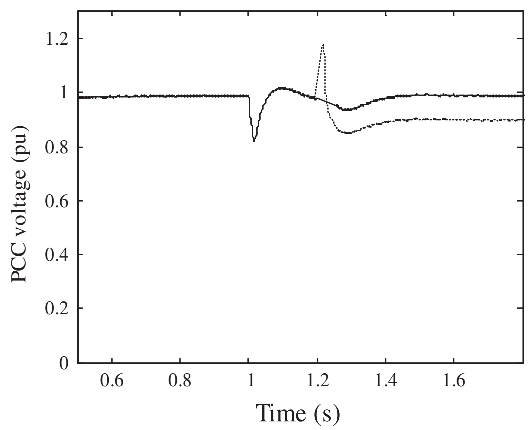

Fig. 3. Voltage profile at PCC (solid line-proposed nonlinear controller, dotted line-conventional PR controller).

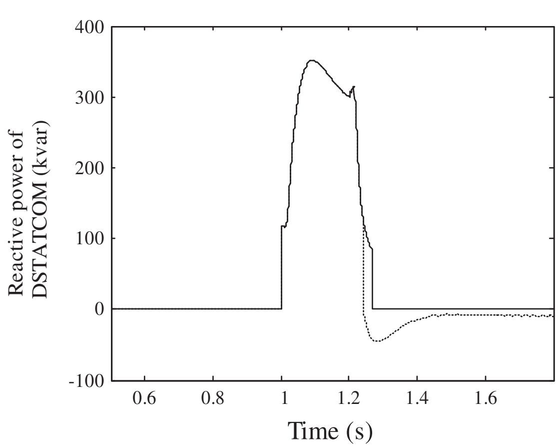

Fig. 4. Reactive power of DSTATCOM (solid line-proposed nonlinear controller, dotted line-conventional PR controller).

cleared at $t = 1.2$ s. If there are no DSTATCOMs within the system, the system voltage will fluctuate during the faulted conditions and sometimes it takes few seconds to few minutes to settle down the voltage to its steady-state value or even the system may become unstable. For the applied fault with considered fault duration, the voltage profile of the PCC is shown in Fig. 3 from where it can be seen that the voltage at the PCC violates the regulation of voltage variations (typically ± 6 per cent) specified by DNSPs when a conventional proportional resonant (PR) controller is used for controlling the DSTATCOM which is shown by dotted line. Moreover, the system is unable to achieve the pre-fault steady-state condition after clearing the fault. An improved voltage profile at the PCC can be obtained with the proposed partial feedback linearizing controller which is also shown in Fig. 3 by solid line. The improved voltage profile is obtained at the PCC due to the regulation of reactive power and DC voltage across the capacitor. The regulation of reactive power and DC voltage with the proposed controller is shown in Figs. 4 and 5, respectively.

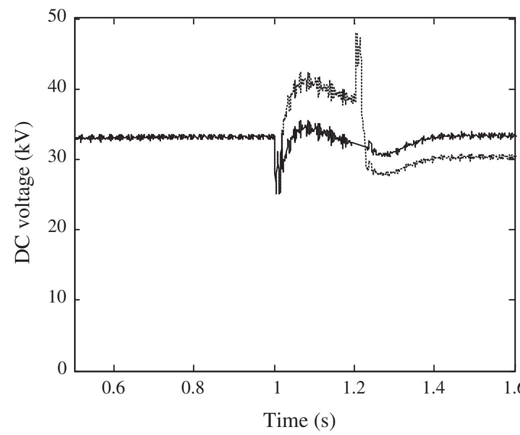

Fig. 5. DC voltage of DSTATCOM (solid line-proposed nonlinear controller, dotted line-conventional PR controller).

6. Conclusion

In this paper, a partial feedback linearizing control scheme for a DSTATCOM is presented which enhances the voltage stability of distribution networks with DG following large disturbances. The proposed controller design approach cancels all possible nonlinearities by transforming a DSTATCOM connected to the network into two decoupled linear subsystems with a stable internal dynamics. The DC voltage of the DSTATCOM and reactive power are controlled to keep the voltage within the specified region. From the simulation results, it is clear that the controller performs better as compared to the conventional PR controller under major disturbances. Future work will deal with the extension of the proposed method by considering the system operating at islanding mode and applying faults on different parts of the system.

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