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Novel control strategy for voltage source converters based on energy function

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Abstract: This paper proposes a nonlinear control strategy for pulse-width modulated voltage source converters (VSCs). A passivity-based approach, resulting from the Lyapunov direct method, is presented for designing an effective nonlinear VSC controller to improve their dynamic behaviors under perturbed conditions. The differential equations of the converters are obtained and then transformed into a $d-q$ frame. Considering the nonlinearity of the transformed equations, the Lyapunov direct method is utilized to find a solution to improve the transient response. The time derivative of the Lyapunov function guarantees that increasing its dissipative term will result in the trajectory of the VSC system returning to the equilibrium point more quickly. The proposed control strategy can be simultaneously applied to multiVSC devices, such as a unified power flow controller (UPFC). Moreover, it is shown that the proposed strategy meets the steady-state requirements without using any other control loop. As an example, a 3-machine system with a UPFC is studied to verify the effectiveness of the proposed strategy.

Key words: Voltage source converter, energy function, passivity based control

1. Introduction

Voltage source converters (VSCs) are the main part of many important devices such as flexible alternating current (AC) transmission system (FACTS), converters of DC transmission systems, custom power devices, and AC-motor drives. Pulse-width modulated (PWM) VSCs provide numerous advantages, such as a sinusoidal input current with controllable power factor, high-quality direct current (DC) output voltage with a small filter capacitor, and the capability of the independent control of active and reactive powers with a bidirectional power flow. Considering the VSC's different applications, different control strategies have been proposed in [1–7]. In the conventional control schemes, both AC and DC voltage regulating functions are implemented by proportional integral (PI)-type cascaded controllers [8]. Since the VSC is highly nonlinear, the linear control approach obviously cannot lead to a better response than a nonlinear control approach. Therefore, several nonlinear control methods have been proposed to design VSC controllers [9–13].

For the first time, a nonlinear control approach has been presented in [9], where the state feedback linearization has been used. In [10], the state feedback linearization has been utilized neglecting the line and switching losses. These assumptions will not tend to give an accurate response, especially at high current and high frequency. As it is presented in this paper, the losses should not be neglected and they should be considered as a key point in the design of an effective controller. Input–output linearization using a number of

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simple tracking outputs is another nonlinear approach that has been used in [11]. However, in [12] it has been proven that the input–output linearization method will lead to parameter uncertainties. In [12], a flatness-based tracking control for the VSC has been proposed, where the nonlinear model is directly compensated without a linear approximation. Although the flatness leads to a straightforward open-loop control design, in comparison with the strategy developed in this paper, it involves complexity. In [13], the VSC energy function has been used to transform VSC nonlinear equations to the linear environment, in which all of the linear criterions are applicable to improve the stability and there is no simplification. Since the transformation process has strictly been involved with VSC-inherent parameters such as VSC transformer inductances and capacitance, the parameter uncertainty will tend to be a huge failure on the control process. Moreover, transforming the nonlinear equations, implementing the necessary linear processes, and the inverse transforming of the control functions require relatively more time and high speed digital signal processors.

One of the sophisticated nonlinear control methods for power converters is the passivity-based approach, which has been presented in [6] and [7]. The VSC can be modeled by nonlinear differential equations in a rotating $d-q$ reference frame. Considering this nonlinearity, the Lyapunov method can be used. The Lyapunov theory introduces the time derivative of the VSC energy function as a suitable criterion for stability analyses. The more the negative value for time derivative of the energy function is, the faster the system trajectory returns to its equilibrium point, or, in other words, we have fast oscillation damping.

In this paper, the direct Lyapunov method is used in order to develop a simple and reliable control strategy to control the VSC switching fire angles. The dissipative term of describing the differential equations of the VSCs is increased, in order to meet the Lyapunov condition for VSC stability improvement or quick damping of VSC power oscillations. It is shown that only one control loop is sufficient to control the transient and steady-state conditions. The proposed strategy is independent of the VSC application and its connection type. Moreover, the suggested strategy can be used for mutliVSC-type devices.

The paper is organized as follows. In Section 2, the VSC model is represented by nonlinear differential equations. In Section 3, the direct Lyapunov method is discussed and then the matrix form of the VSC equations is presented. In Section 4, the Lyapunov theory is applied to the VSC model and the desired control function is obtained to meet the transient and steady-state constraints. As an example, a unified power flow controller (UPFC) is studied in Section 5. The simulation results verify the effectiveness of the proposed control strategy.

2. The model of voltage source converters

The most popular type of VSC is illustrated in Figure 1. By controlling the firing angle of the switches, the VSC will generate the balanced and controlled 3 phase voltages. The connection of the VSC to the grid is via a transformer. Depending upon the application of the VSC, its transformer can have a series or shunt connection. Assuming a shunt connection, shown in Figure 1, the VSC can be modeled by conventional mathematical relationships. The bipolar switching function in one leg of the converter is defined, as follows:

$$u_j = \begin{cases} 1, & S_j: \text{ closed} \\ 0, & \bar{S}_j: \text{ closed} \end{cases} \qquad j = a,\, b \text{ and } c. \tag{1}$$

Kirchhoff's voltage law for the AC side of the converter yields the following equations:

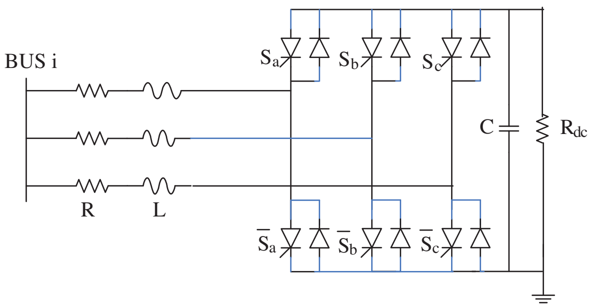

Figure 1. Basic topology of a typical VSC.

$$\begin{aligned} L\tfrac{di_a}{dt} + Ri_a + u_a V_{dc} = e_{ia} \\ L\tfrac{di_b}{dt} + Ri_b + u_b V_{dc} = e_{ib} \\ L\tfrac{di_c}{dt} + Ri_c + u_c V_{dc} = e_{ic} \end{aligned} \quad , \tag{2}$$

where i_a, i_b and i_c are the 3 phase currents of the AC side of the VSC; e_{ia}, e_{ib} and e_{ic} are the 3 phase voltages of bus i; V_{dc} and R_{dc} are the VSC capacitor voltage and capacitor resistance, respectively; and R and L are the resistance and leakage inductance of the VSC connecting transformer. Moreover, the switching resistance is included in R. Kirchhoff's current law for the DC side of the converter is as follows:

$$C\frac{dV_{dc}}{dt} - (u_a i_a + u_b i_b + u_c i_c) + \frac{V_{dc}}{R_{dc}} = 0. \tag{3}$$

The 3 phase voltages of the VSC bus, i.e. bus i, are nominated as a reference frame, in which the 3 phase currents and voltages are represented in direct and quadrature formats, i.e, $d-q$ format. This task is fulfilled by synchronizing the phase-locked loop (PLL) to the positive-sequence component of the bus i voltages. The PLL provides the synchronous reference angle, which is required to compute the $d-q$ axis components of the 3 phase parameters. Transforming the synchronous $d-q$ reference frame, Eqs. (2) and (3) are written as follows:

$$\begin{aligned} L\tfrac{di_d}{dt} + Ri_d - \omega L i_q + V_{dc} u_d = E_i \\ L\tfrac{di_q}{dt} + Ri_q + \omega L i_d + V_{dc} u_q = 0 \end{aligned} \quad , \tag{4}$$

$$C\frac{2dV_{dc}}{3dt} - (i_d u_d + i_q u_q) + \frac{2V_{dc}}{3R_{dc}} = 0, \tag{5}$$

where i_d and i_q represent the 3 phase currents in the $d-q$ reference frame and E_i is the direct component of the bus i voltage, which, in fact, is represented in its own reference frame. Therefore, E_i is simply the *rms* voltage value of phase A in bus i and u_d and u_q are the switching control functions in the $d-q$ reference frame.

The above-mentioned differential equations describe well the VSC behavior. Since the 'bilinear' form of the nonlinearity is obvious in these equations, the dynamical analysis of such systems by conventional linear techniques cannot adequately satisfy the desired results. Therefore, a more appropriate method should be used. Among dynamic analyzing methods, the direct Lyapunov function, i.e. energy function, in electrical and mechanical systems has emerged as a reliable approach to properly deal with the nonlinearities of such equations. Moreover, from a plant controlling point of view, the study of the energy function is sufficient for the system stability determination. This method does not directly deal with the straightforward solution of the differential equations. However, it offers the system energy function as a suitable criterion to discuss the dynamic behavior of the system that is described by the differential equations. In other words, the direction of the system trajectory toward the equilibrium point(s) or toward unstable points can be recognized due to the sign of the time derivative of the energy function.

3. Direct Lyapunov method

Considering the VSC described in Eqs. (2) and (3), the corresponding Lyapunov function or energy function, $w(x)$, can be simply defined. x is the state vector as: $x^T = [x_1, x_2, x_3] = [i_d, i_q, V_{dc}]$.

Any disturbance in the power grid or in the load side of the adjustable speed drives should result in a power imbalance in the AC and DC sides of the converter. This power perturbation moves the VSC system trajectory from the prefault stable equilibrium point to a transient point, $x_i(t)$, which possesses a higher energy level than that of the postfault equilibrium point. Regarding the transiency and positiveness characteristics of the energy function, the negative value of $\dot{w} = dw/dt$ can be interpreted as a reduction in $w(x)$ and movement toward its minimum value that evolves at the postfault equilibrium point, x_i^*. Consequently, the more negative value of $\dot{w}$ means that the VSC returns to the equilibrium point, x_i^*, rapidly (i.e. the system has a better oscillation damping) [14]. Eqs. (4) and (5) can be written into matrix form as follows:

$$D\dot{x} + [\zeta_1 + \zeta_2 (u)]\, x + \Re x = \varepsilon, \tag{6}$$

where u is the control input vector that is defined as: $u^T = [u_d, u_q]$ and the other parameters of Eq. (6) are given as follows:

$$D = \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & C \end{bmatrix} \quad \zeta_1 = \begin{bmatrix} 0 & -\omega L & 0 \\ \omega L & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\zeta_2 = \begin{bmatrix} 0 & 0 & u_d \\ 0 & 0 & u_q \\ -u_d & -u_d & 0 \end{bmatrix} .$$

$$\Re = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & \frac{1}{R_{dc}} \end{bmatrix}, \varepsilon = \begin{bmatrix} E_i \\ 0 \\ 0 \end{bmatrix}$$

Here, D is a positive-definite diagonal matrix, ζ_1 and ζ_2 are the interconnection matrices with switches, and ε is the voltage source vector corresponding to the AC system. $\Re$ is the VSC dissipative matrix. Considering the skew-symmetry property, matrices ζ_1 and ζ_2 have no effects on the energy function.

4. VSC control strategy

The Lyapunov or energy function for a typical VSC system can be written as the following equation:

$$w(x) = \frac{1}{2} x^T D x. \tag{7}$$

The time derivative of the VSC energy function is as follows:

$$\dot{w}\left(x\right) = x^T D\dot{x}. \tag{8}$$

Multiplying Eq. (6) by x^T results in the following equation:

$$x^T D\dot{x} + x^T \left[\zeta_1 + \zeta_2\left(u\right)\right] x + x^T \Re x = x^T \varepsilon. \tag{9}$$

The first term in Eq. (9), i.e. $x^T D\dot{x}$, is the time derivative of the energy function and can be replaced by $\dot{w}\left(x\right)$. Hence, Eq. (9) is rewritten as follows:

$$\dot{w}\left(x\right) = x^T \varepsilon - x^T \left[\zeta_1 + \zeta_2\left(u\right)\right] x - x^T \Re x. \tag{10}$$

It can be easily proven that the term $-x^T\left[\zeta_1 + \zeta_2\left(u\right)\right] x$ is equal to zero. Therefore, Eq. (10) presents the power balance between the AC and DC sides of the VSC. The power balance in both sides of the converter exists as long as the VSC operates in steady state. However, any deviations in state variables of both the converter and the grid will disturb the mentioned balance. Therefore, the minimization of Eq. (10) is being sought. By a slight modification, the cost function is written as Eq. (11), which is in fact the time derivative of the energy function.

$$\dot{w}\left(x\right) = x^T \varepsilon - x^T \Re x \tag{11}$$

The more negative value in $\dot{w}\left(x\right)$, according to the Lyapunov theory, results in the fast return of the VSC system trajectory to the equilibrium (or stable point). Thus, the desired result will be satisfied by boosting the dissipative term of Eq. (11), i.e. $x^T \Re x$, into $x^T \Re_d x$, where $\Re_d$ is the desired resistance and is defined as $\Re_d = \Re + r$, and r is the virtually added resistance, as follows:

$$r = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & r_3 \end{bmatrix}.$$

Even though the boosted dissipative term of Eq. (11) will improve the damping of the system oscillations, it also will disturb the system equilibrium point of Eq. (6) in the steady-state condition. To meet both the transient and steady-state constraints, Eq. (6) is rewritten for steady state as follows, while it includes the desired resistance:

$$D\dot{x}^* + \left[\zeta_1 + \zeta_2\left(u\right)\right] x^* + \Re_d x^* = \varepsilon \tag{12}$$

or

$$D\dot{x}^* + \left[\zeta_1 + \zeta_2\left(u\right)\right] x^* + \Re x^* + r x^* = \varepsilon, \tag{13}$$

where x^* stands for the state vector in the steady-state condition and is named the reference vector. Moreover, the state vector at the steady state has no variation; therefore, the term $D\dot{x}^*$ in Eq. (13) is zero. Comparing Eqs. (13) and (6), it is obvious that the term rx cannot be seen in Eq. (6). Hence, the term rx is subtracted from Eq. (13) as follows:

$$\left[\zeta_1 + \zeta_2\left(u\right)\right] x^* + \Re x^* + r x^* - r x = \varepsilon. \tag{14}$$

It is clear that the term $rx - rx^*$ in Eq. (14) becomes zero when the VSC is in steady-state condition (or x and x^* have the same values). In other words, the additive resistance emerges only when the state vector deviates from its reference value. The decomposition of Eq. (14) and then finding the control input vector, u, results in the VSC control law as follows:

$$\begin{aligned} u_d &= \tfrac{-1}{x_3^*}\left[Rx_1^* - \omega L x_2^* + r_1\left(x_1^* - x_1\right) - E_i\right] \\ u_q &= \tfrac{-1}{x_3^*}\left[Rx_2^* + \omega L x_1^* + r_2\left(x_2^* - x_2\right)\right] \end{aligned} . \tag{15}$$

This control law (strategy) is a sophisticated strategy that contains only the algebraic terms that make the control strategy more easy and reliable to be applied. Moreover, this control strategy is adequately suited for the steady-state condition. Depending upon the purpose of the VSC application, the reference values of the VSC state variables are obtained from the results of the load (power) flow program or they are obtained from some vital grid constraints, like keeping the bus voltage at the specified value. Changing the reference values, in steady state, will cause the term $r\left(x - x^*\right)$ to emerge and change the VSC switching function so that the VSC operates at the new point of steady-state operation.

5. Unified power flow controller

As an example of a VSC application in a power system, a UPFC, using 2 VSCs, shown in Figure 2, has been studied. The UPFC has been developed as an effective power flow controller with the capabilities of terminal voltage regulation, series line compensation, and phase angle regulation [15–19].

Moreover, it has been employed for transient stability and power swing mitigation improvement [20–24]. The control law, as presented in Eq. (15) for the individual VSC, is applied for controlling both VSCs of the UPFC, as follows:

$$\begin{aligned} u_{dsh} &= \tfrac{-1}{x_5^*}\left[R_{sh}x_1^* - \omega L_{sh} x_2^* + r_1\left(x_1^* - x_1\right) - E_i\right] \\ u_{qsh} &= \tfrac{-1}{x_5^*}\left[R_{sh}x_2^* + \omega L_{sh} x_1^* + r_2\left(x_2^* - x_2\right)\right] \\ u_{ds} &= \tfrac{-1}{x_5^*}\left[R_s x_3^* - \omega L_s x_4^* + r_3\left(x_3^* - x_3\right) - E_i + e_{dj}\right] \\ u_{qs} &= \tfrac{-1}{x_5^*}\left[R_s x_4^* + \omega L_s x_3^* + r_4\left(x_4^* - x_4\right) + e_{qj}\right] \end{aligned} . \tag{16}$$

The variables and parameters with subscripts sh and s denote the shunt and series branches, respectively. Hence, the state variables are: $x^T = [x_1, x_2, x_3, x_4, x_5] = [i_{dsh}, i_{qsh}, i_{ds}, i_{qs}, V_{dc}]$.

The steady-state reference parameters for the UPFC series branch, i.e. x_3^* and x_4^*, are determined according to the differences between the line active and reactive powers with their reference values. In other words, the error signals ($P_{ref} - P_L$ and $Q_{ref} - Q_L$) are fed into the PI controller to create the control reference signals, x_3^* and x_4^*.

Two constraints must be satisfied by the shunt branch of the UPFC in steady state. The first is providing the active power for the series branch and the second is adjusting the desired voltage at bus i, which can be implemented by controlling the shunt reactive power, Q_{shi}.

The voltage error signal, i.e. $V_{refi} - V_i$, is fed into the PI controller to create a control reference signal, x_1^*, which in turn can control the shunt branch reactive power. The same task is fulfilled to obtain the x_2^* by applying the DC voltage variation, i.e. $V_{dcref} - V_{dc}$, to the PI controller. x_5^* is determined considering the UPFC design for the specified power and energy capacity. Figure 3 illustrates the UPFC controller block diagram using the proposed strategy.

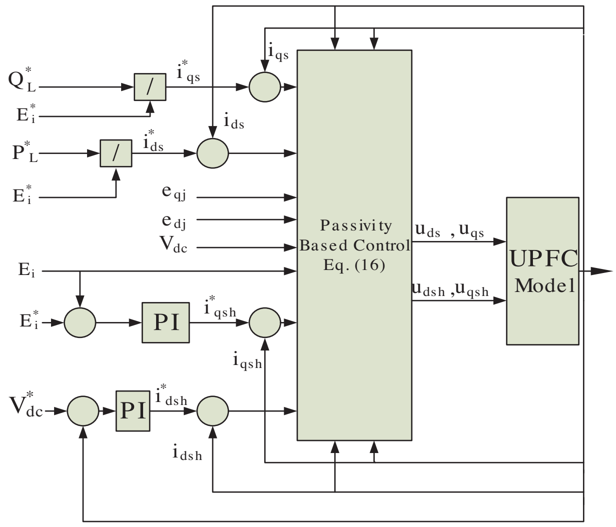

Figure 2. UPFC schematic diagram.

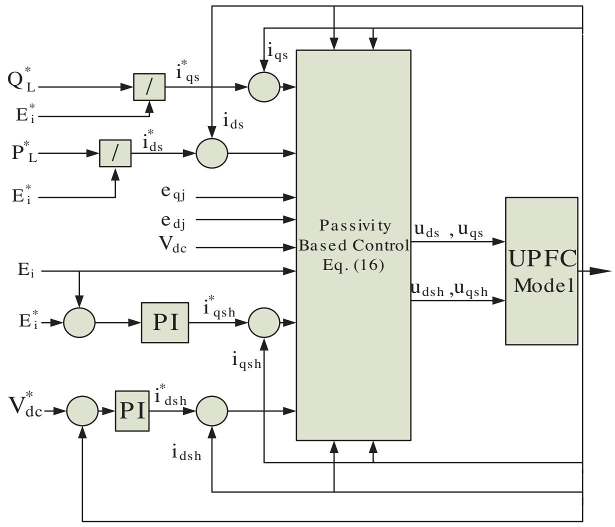

Figure 3. UPFC controller block diagram.

6. Simulation results

The effectiveness of the proposed control strategy was studied in a 3-machine test system [14]. The UPFC is used as a controller to damp the oscillations. The single line diagram of the 3-machine system is shown in Figure 4. Generator G3 is a large unit and is considered an infinite bus-bar. Generators G1 and G2 are driven by hydraulic and steam turbines, respectively. Therefore, the swings of generator G2 are faster than those of G1. A temporary 3-phase short-circuit fault, occurring at 1 s and clearing at 1.15 s, at bus B5 has been simulated while the UPFC has been installed in line L4.

The active powers of the generators have been studied with and without the UPFC. The simulation results are shown in Figures 5 and 6. The added dissipative terms for the shunt branch, r_1 and r_2, are 35% of nominal resistance of the shunt branch and r_3 and r_4 are 30% of the nominal resistance of the series branch. In normal operation mode, generators G1 and G2 produce 130.3 MW and 260.5 MW of active power, respectively. As shown in Figures 5 and 6, the application of the UPFC results in the reduction of the oscillation damping time. Moreover, when compared with the uncontrolled system, the results show 58% and 60% reductions in

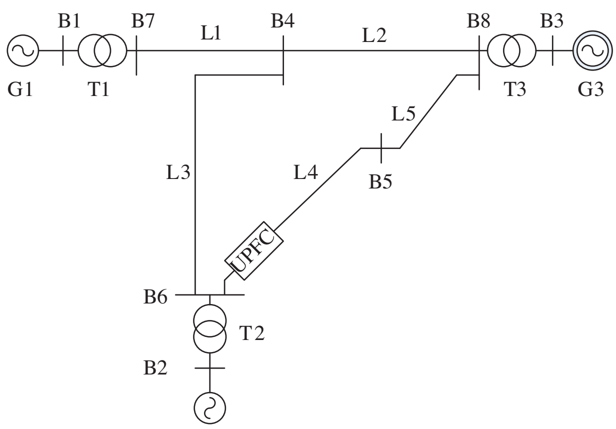

Figure 4. The 3-machine test system.

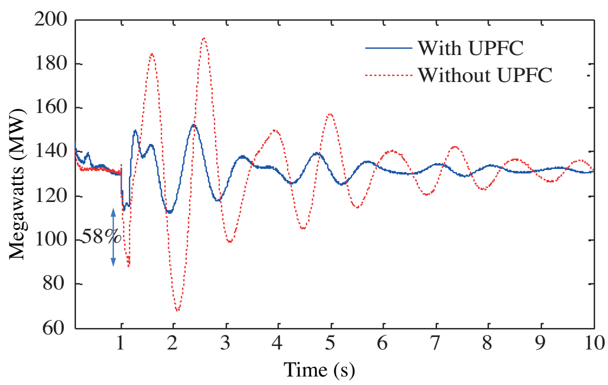

Figure 5. Generator G1's active power, with and without the UPFC (with added dissipative terms).

first negative swings. The active power of line L4 is shown in Figure 7 in both cases (with and without the UPFC). It interestingly demonstrates that the UPFC is a strong barrier against the power oscillations when there are added dissipative terms in the control paths.

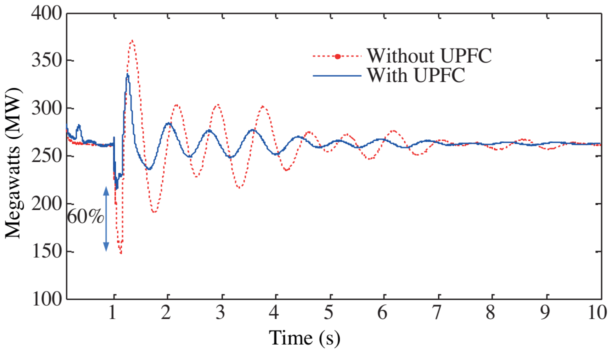

Figure 6. Generator G2's active power, with and without the UPFC (with added dissipative terms).

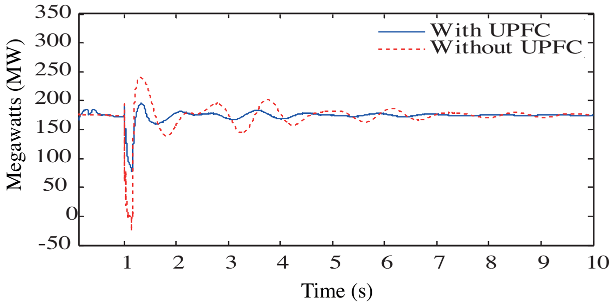

Figure 7. Active power of line L4.

The same simulation has been repeated while the there are no added resistances and the UPFC has been controlled only by the conventional PI controllers. The results are shown in Figures 8 and 9. Comparing the simulation results in both cases, with and without the dissipative terms, truly verifies the effectivenes of the proposed VSC control strategy.

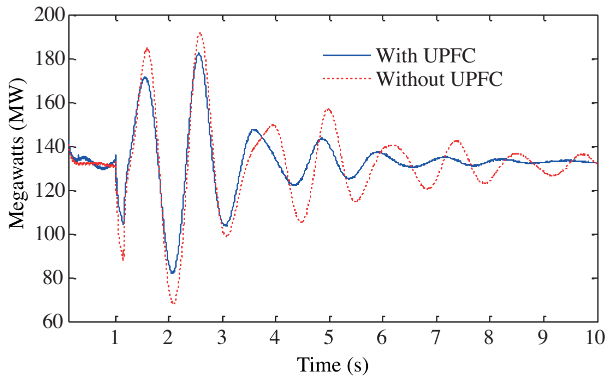

Figure 8. Generator G1's active power, with and without the UPFC (with no dissipative terms).

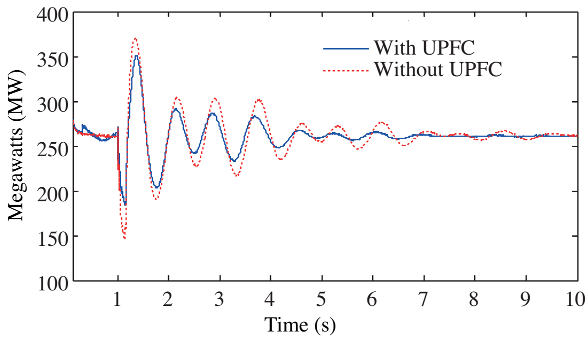

Figure 9. Generator G2's active power, with and without the UPFC (with no dissipative terms).

7. Conclusions

In this paper, a model of the VSC in $d-q$ reference frame has been presented. The direct Lyapunov method or energy function has been used to extract a suitable control strategy for VSCs that can improve the transient response. In the proposed strategy, the resistivity term has been added to the VSC's intrinsic resistance so that the damping agent increases and transient time elapsed quickly. The developed control strategy, for improving the oscillation damping, has met the steady-state requirements appropriately. As an example, a UPFC unit installed in a power system has been studied to verify the effectiveness of the proposed strategy. It was shown that the UPFC can damp the power oscillations that resulted from a sudden short-circuit fault.

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