TRANSIENT STABILITY IMPROVEMENT OF POWER SYSTEM USING UPFC AND FEEDBACK LINEARIZATION CONTROL

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Since demand for electrical energy is increasing day to day, applying improved plans to reach more reliable and secure power system are inevitable. Using Flexible AC Transmission System (FACTS), it is possible to control the transmitted power through transmission lines and improve transient stability of the power system. In this paper, a suitable control method based on feedback linearization is proposed to guide the Unified Power Flow Controller (UPFC). In order to verify the ability of this method on transient stability improvement, simulation results of a multi-machine power system is presented.

Keywords: UPFC, Transient stability, Feedback linearization, Transient energy function.

1. Introduction

Traditionally, transmitted power through transmission lines is limited due to thermal limits, voltage drop and stability limits. However it is possible to exceed thermal limits during short-time interval. In order to exploit transmission lines economically, transmitted power through the lines have to be increased using FACTS devices.

Today because of increasing need for electric energy in one hand and limitation in transmission network development and limitation in adding transmission lines for economic reasons on the other hand, transmission lines should be exploited in useful condition and near the stability limits. As a result, stability limit of system decreases. Emerging the FACTS devices increase this stability limits. Nowadays FACTS are placed in the network as series, parallel, and series-parallel [1-2]. UPFC is the most versatile FACTS device is placed in the network as series-parallel [3-4]. Till now many methods have been proposed to control UPFC and

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other FACTS equipments in order to improve transient stability of the power systems [5]. These works ignored power system and UPFC nonlinearities. In [10], transient stability of the power system is improved using the sensitivity estimation techniques with the assumptions such as: the internal voltages of generators don't change immediately and an active power flow is proportional to difference between the voltage phases at ends of the transmission line. These assumptions cause approximation in control signal computation that destroys the overall system performance. In [11-12] the effect of UPFC on transient stability of power system is investigated, however [11-12] only analyze the transient stability and use a simple model for UPFC. In [13] model of UPFC is given and simple controllers are proposed using conventional PI control; but these simple controls do not guarantee the high performance of the overall power system and may be failed in transient.

Feedback Linearization control method is a well known and powerful method to control nonlinear systems [6]. The most important features of this method are its high speed in tracing the input signals and, easiness of linearized system control [7]. In this paper, considering nonlinearity aspects of power systems, a nonlinear control method based on feedback linearization method is proposed to control UPFC in order to improve transient stability margins of power system. In order to improve transient stability, transient energy function of UPFC is optimized such that highest values for transient stability margins are obtained. Although, using energy function is a suitable method for transient stability studies, complexity of nonlinear equations of power system results in a time consuming numeric work. To reduce computation time and burden, feedback linearization method is applied to convert nonlinear equations to linear ones. The main contribution of this paper is the combination of feedback linearization with energy function method to improve the transient stability of the power system. For this purpose state space model of UPFC is presented in section 2. Next, feedback linearization control is applied on the obtained state space model in section 3. In section 4, control laws are presented to improve network transient stability. In section 5 the selected multi machine power system to test and investigate the proposed method is introduced and its data and parameters are given. Finally, in order to investigate capability of the proposed method, some simulations have been carried out and the obtained results are reported in section 6.

2. State space equation of UPFC

General structure of UPFC is shown in Fig. 1.

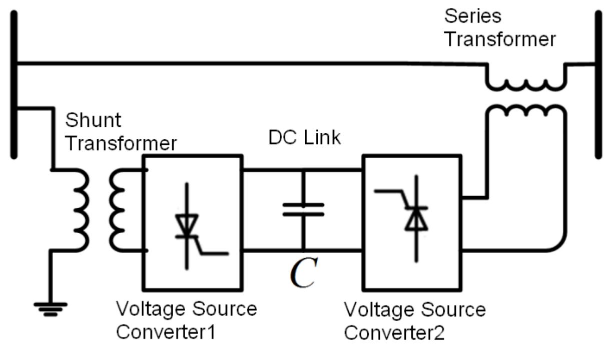

Fig. 1. Structure of UPFC.

UPFC includes two inverters. The first one behaves as a Synchronous Static Compensator (STATCOM) and, is used to inject a sinusoidal current to the Network. The other inverter is used to add a series sinusoidal voltage in the line. So it works as Static Series Synchronous Compensator (SSSC). Voltage amplitude and angle of the connected nodes can be set on desired values by controlling each inverter separately. Since UPFC can control power flow through each network lines, it could be helpful to improve transient stability of the network. Regarding to application, different models have been presented for UPFC [1, 3]. One of these models is based on the injected currents in dqo space and is shown in Fig. 2.

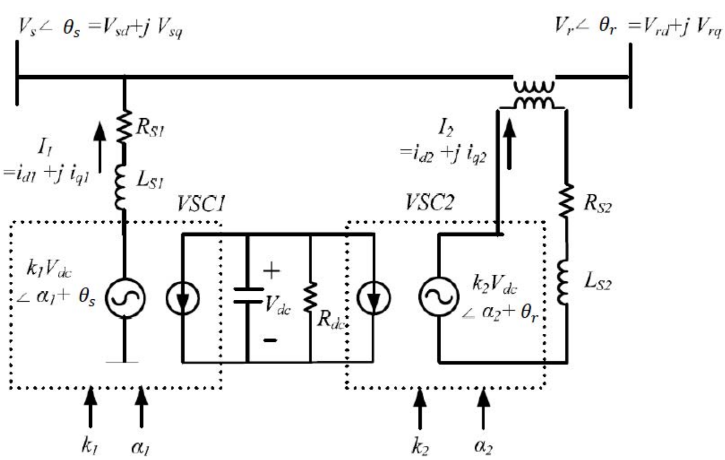

Fig. 2. UPFC equivalent circuit

The series and parallel injected currents are I_1 and I_2, respectively. dq components of I_1 and I_2 are considered as real and imaginary parts of vectors I_1

and I_2. Inverters output voltages are controlled by amplitude modulation index (k) and phase angle modulation index (α). The applied switching algorithm is PWM. Considering real and imaginary part of I_1 and I_2 and DC link voltage of compensator state variables, then equations of system state will be presented as (1) [3]. Where, R_{s1} / R_{s2} and L_{s1} / L_{S2} are the resistance and reactance of the shunt/series transformer. C_{dc} presents the DC-link capacitor and R_{dc} models inverters losses. ω_s is synchronous speed or network frequency in rad/sec, and ω is angular speed of the synchronous generator whose stability margin should be improved.

$$\frac{1}{w_s}\begin{bmatrix} L_{s1} & 0 & 0 & 0 & 0 \\ 0 & L_{s1} & 0 & 0 & 0 \\ 0 & 0 & L_{s2} & 0 & 0 \\ 0 & 0 & 0 & L_{s2} & 0 \\ 0 & 0 & 0 & 0 & C_{dc} \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} -R_{s1}x_1 + \frac{\omega}{\omega_s}x_2 - V_{sd} \\ -R_{s1}x_2 - \frac{\omega}{\omega_s}x_1 - V_{sq} \\ -R_{s2}x_3 - \frac{\omega}{\omega_s}x_4 - (V_{sd} - V_{rd}) \\ -R_{s2}x_4 - \frac{\omega}{\omega_s}x_3 - (V_{sq} - V_{rq}) \\ -x_5/R_{dc} \end{bmatrix} + \begin{bmatrix} x_5 & 0 & 0 & 0 \\ 0 & x_5 & 0 & 0 \\ 0 & 0 & x_5 & 0 \\ 0 & 0 & 0 & x_5 \\ -x_1 & -x_2 & -x_3 & -x_4 \end{bmatrix}\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} \quad (1)$$

Also, system state variable vector, x, and system input vector are defined as follows: (2)

$$x = [i_{d1} i_{q1} i_{d2}\ i_{q2}\ V_{dc}]^T$$

$$u = [u_{d1} u_{q1} u_{d2}\ u_{q2}]^T \quad (3)$$

$$\begin{cases} u_{d1} = k_1 \cos(\alpha_1 + \theta_s) \\ u_{q1} = k_1 \sin(\alpha_1 + \theta_s) \\ u_{d2} = k_2 \cos(\alpha_2 + \theta_s) \\ u_{q2} = k_2 \sin(\alpha_2 + \theta_s) \end{cases} \quad (4)$$

3. Feedback linearization control

Feedback linearization method is used to change a non-linear system to a completely or partly linear system. Considering the following single-input single-output nonlinear system as follow:

(5)

$$\dot{x} = f(x,u)$$
$$y = h(x) \tag{6}$$

State-input linearization method solves this problem in two steps. At first, a state transformation such as z=z(x), and an input transformation such as u=u(x,v) should be found such that, they transform the dynamics of the non-linear system into the dynamics of a time-invariant linear system which is represented by =Az+bv. Next, second step is the design of v by standard methods of linear control such as optimum control, robust control, LQR, and etc. Before implementing nonlinear control method for UPFC, state equations of system in (1) have been written as canonical non-linear form:

$$\begin{cases} \dot{x} = f(x) + \sum_{i=1}^{4} g_i(x)u_i \\ y = h(x) \end{cases} \tag{7}$$

f(x) and g(x) have been represented as follow:

$$f(x)=\begin{bmatrix} a_1x_1 + bx_2 - c_1V_{sd} \\ a_1x_2 - bx_1 - c_1V_{sq} \\ a_2x_3 + bx_4 + c_2(V_{sd} - V_{rd}) \\ a_2x_4 - bx_3 - c_2(V_{sq} - V_{rq}) \\ -\frac{dx_5}{R_{dc}} \end{bmatrix} \qquad g(x) = \begin{bmatrix} c_1x_5 & 0 & 0 & 0 \\ 0 & c_1x_5 & 0 & 0 \\ 0 & 0 & c_2x_5 & 0 \\ 0 & 0 & 0 & c_2x_5 \\ -dx_1 & -dx_2 & -dx_3 & -dx_4 \end{bmatrix} \tag{8}$$

where:

$$a_1 = \frac{-R_{s1}\omega_s}{L_{s1}},\ a_2 = \frac{-R_{s2}\omega_s}{L_{s2}}, c_1 = \frac{w_s}{L_{s1}}, d = \frac{\omega_s}{c_{dc}}$$
$$c_2 = \frac{\omega_s}{L_{s2}}, b = \omega \tag{9}$$

So in the first step, a state transformation is needed which transforms the non-linear equations into the canonical form ones. This transformation is proposed as follow:

$$Z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} = \phi(x) = \begin{bmatrix} h(x) \\ L_f h(x) \\ \phi_3(x) \\ \phi_4(x) \\ \phi_5(x) \end{bmatrix} = \begin{bmatrix} h(x) \\ L_f h(x) \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{10}$$

Selection of φ_3, φ_4 and φ_S is similar to selection of state variables x_2, x_3 and x_4. Besides, $L_f h(x)$ is lie derivative of h(x) function relative to f(x). The key point in this transformation is suitable selection of function h(x), in this paper h(x) is similar to Lyapunov function and is considered as follow:

(11)

$$h(x) = \frac{L_{s1}}{2}(x_1^2 + x_2^2) + \frac{L_{s2}}{2}(x_3^2 + x_4^2) + \frac{C_{dc}}{2}x_5^2$$

Using (1) and (10), the state equations of the system in new state variables are given by:

$$\begin{cases} \dot{z}_1 = z_2 \\ \dot{z}_2 = v_1 \\ \dot{z}_3 = v_2 \\ \dot{z}_4 = v_3 \\ \dot{z}_5 = v_4 \end{cases} \quad (12)$$

These equations have been transformed into the linear form =Az+bv where for matrices A and B we will have:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (13)$$

Now that non-linear system (1) is transformed into a linear one, in second step new inputs of linearized system should be properly controlled. It is noticed that for this purpose all linear control methods are applicable. More information about the Lie derivatives are reported in appendix 8.1.

4. Control rules

As in this paper, improving of transient stability is the focus of attention, thus controlling the new inputs has been done for attaining this aim. Besides, with regarding this fact that transient energy function of system is a proper means for studying the greatest most transient stability margin, the following energy function of UPFC is employed [8]:

$$V_{UPFC} = \frac{V_T}{X_S}\left(V_i\cos(\varphi_T) - V_j\cos\left(\theta_{ij} + \varphi_T\right)\right) + V_i I_q \quad (14)$$

Where V_j and V_j are buses voltages in begin and end of the compensator, θ_{ij} is the angle difference between two buses and I_q is injected imaginary current by the parallel transformer with x_s. According to the following equation, V_T and φ_T are also directly related to state variables x_3 and x_4:

(15)

$$V_T \measuredangle \phi_T = j\omega R_{s2} I_2$$

If the aim is to improve the transient stability, two control parameters V_T and I_q in their maximum values should be regulated proportional to nominal values, then V_T^* and I_q^* values are desirable. As UPFC injects more energy into the network, there will be more security margin of transient stability. Therefore energy function of UPFC can be used for optimum controlling UPFC to attain transient stability. Consequently φ_T is determined such that energy function UPFC becomes maximum in relationship (14). For this purpose, φ_T in relationship (14) is derived and equated to zero and is calculated.
Therefore for improving the transient stability and maximizing energy function, V_T^* , I_q^* and φ_T^* value have been calculated and with regarding to relationship(15) and $I_q = x_2$, obtained values for x_2^* x_3^*, and x_4^* have been considered in controlling inputs of linearized system. So parameters x_1^* and x_S^* should be regulated to their nominal values.

Finally by inverse state transformation, inputs suitable for enforcing the non-linear system are obtained as follow:]

$$u = \begin{bmatrix} L_{g1}L_f h(x) & L_{g2}L_f h(x) & L_{g3}L_f h(x) & L_{g4}L_f h(x) \\ L_{g1}\phi_3(x) & L_{g2}\phi_3(x) & L_{g3}\phi_3(x) & L_{g4}\phi_3(x) \\ L_{g1}\phi_4(x) & L_{g2}\phi_4(x) & L_{g3}\phi_4(x) & L_{g4}\phi_4(x) \\ L_{g1}\phi_5(x) & L_{g2}\phi_5(x) & L_{g3}\phi_5(x) & L_{g4}\phi_5(x) \end{bmatrix}^{-1} \begin{bmatrix} v_1 - L_f^2 h(x) \\ v_2 - L_f\phi_3(x) \\ v_3 - L_f\phi_4(x) \\ v_4 - L_f\phi_5(x) \end{bmatrix} \quad (16)$$

5. Power system selected for Simulation

To show the performance and behavior of power system with the proposed control method, WSCC multi machine benchmark given in [9] is considered.
Selected multi-machine system has 9 buses and 3 machines which are shown is Fig. 3 and its parameters are given in the appendix 8.2. This system has 9-bus, 3 transformers and 3 synchronous generators whose locations are shown in Fig. 3.

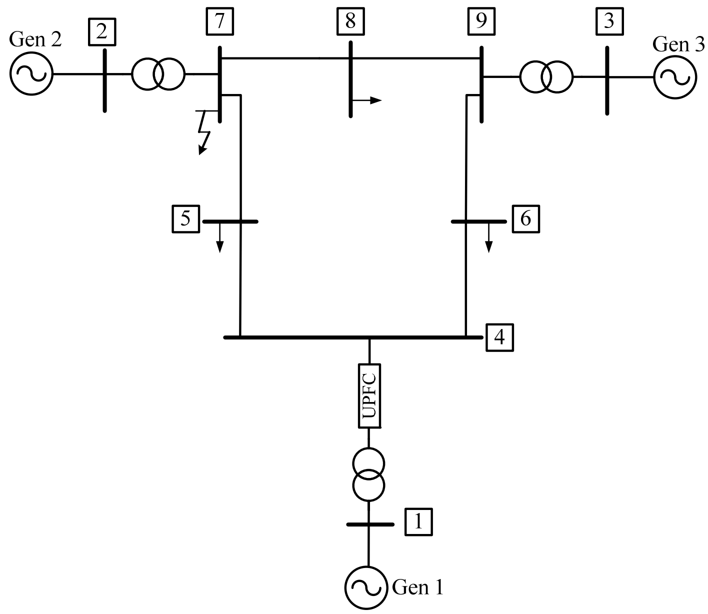

Fig. 3. Schematic of multi machine system

6. Simulation Results: Performance of system in the event of fault

In this section to show the accuracy of the presented method, performance of the multi-machine system in Fig. 3 under a 3-phse short circuit fault in operational power system has been studied. To illustrate the effect of compensator on transient stability improvement, system response to short circuit fault is presented in presence of UPFC and without it in Fig. 4.

Investigation of transient stability is carried out in the first oscillation by evaluating critical time of fault removal. Critical time of fault removal means acceptable time duration for removing the occurred fault without system instability. To find the critical time of fault removal, step by step method has been used in which fault time is increased gradually till reach the critical time is obtained. Fault location is considered near bus No.7. With this method critical time of fault removal for the considered system when there is no compensation, is obtained as 117ms. It is obvious that if fault removal time is considered more than 117 ms, system will become unstable. The simulation results for a 134 ms fault have been shown in Figs. 4, 5 and 6.

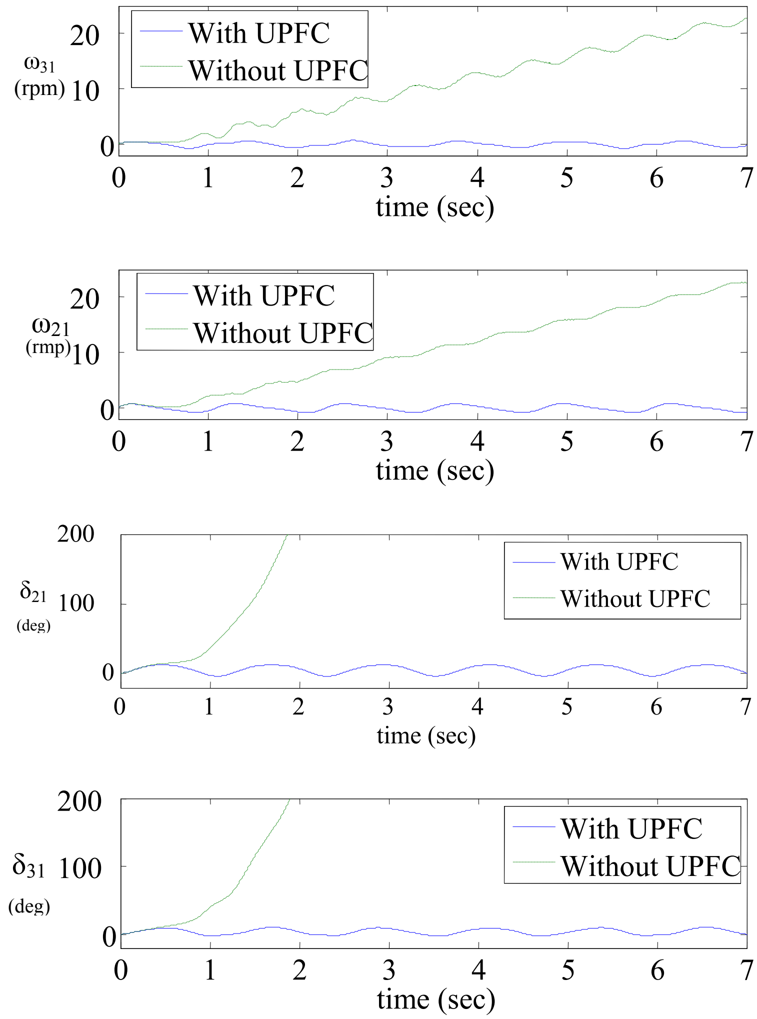

Fig. 4. Rotor speed and angle during 3-phase fault with and without UPFC

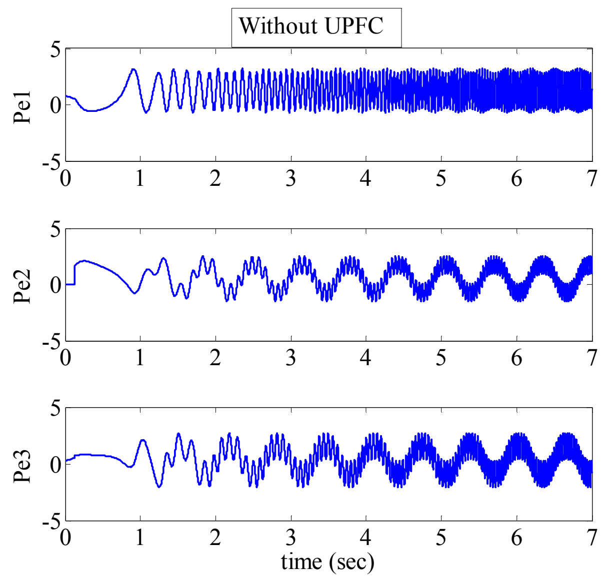

Fig. 5. Per-unit Active power during 3-phase fault without UPFC

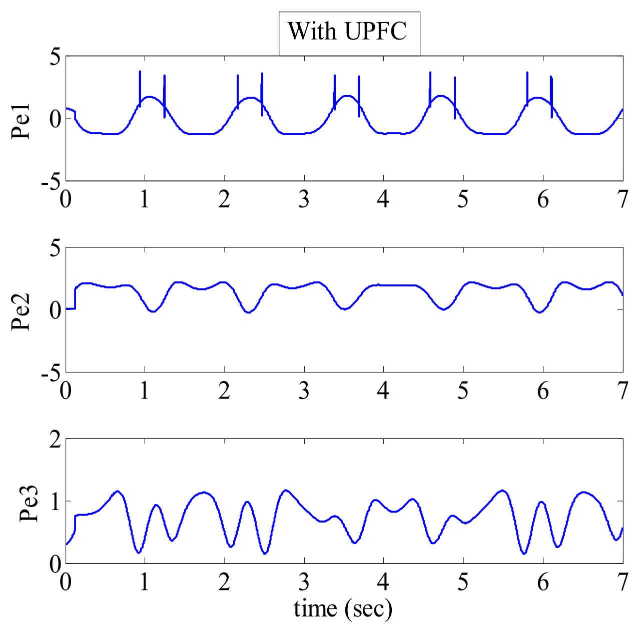

Fig. 6. Per-unit Active power during 3-phase fault with UPFC

Of course the uncompensated system is unstable while the system equipped with UPFC and proposed controller is stable. In these figures, generator

1 is selected as reference generator and variables δ and ω are reported due to this reference. The active powers are illustrated in Figs. 5 and 6 without and with UPFC respectively. Figs. 5 and 6 shows that UPFC decreases swing power oscillations. So the stress on the power system equipments will be alleviated. Results show that in the same condition, system without compensator is unstable and applying the proposed controller and UPFC enhances the system stability.

7. Conclusion

In this paper, a state space mathematical model is used to represent UPFC system. In addition, using feedback linearization method, a state transformation is employed to transform nonlinear equations to linear relations. We used pole placement methods to apply the control laws. Suitable input signals are calculated by inverse transformation of the states. Transient energy function of system as a proper means for studying the greatest most transient stability margin is proposed to improve the transient stability. Simulation results verified the efficiency of mentioned method on a multi-machine system. Simulation results are obtained with and without UPFC. Using the proposed control, the oscillations in active power are decreased significantly.

8. Appendix

8.1. Lie derivatives

$$L_f h(x) = \nabla h(x).f(x) = a_1 L_{s1}(x_1^2 + x_2^2) + a_2 L_{s2}(x_3^2 + x_4^2) - c_1 L_{s1} a_1 L_{s1}\big(x_1 V_{sd} + x_2 V_{sq}\big) + c_2 L_{s2}\left(x_3(V_{sd} - V_{rd}) + x_4\big(V_{sq} - V_{rq}\big)\right) - \frac{d.C_{dc}}{R_{dc}} x_5^2$$

$$L_{g1} L_f h(x) = x_5\left(2a_1 c_1 L_{s1} x_1 - c_1^2 L_{s1} V_{sd} + \frac{2d^2 C_{dc}}{R_{dc}} x_1\right)$$

$$L_{g2} L_f h(x) = x_5\left(2a_1 c_1 L_{s1} x_2 - c_1^2 L_{s1} V_{sq} + \frac{2d^2 C_{dc}}{R_{dc}} x_2\right)$$

$$L_{g3} L_f h(x) = x_5\left(2a_2 c_2 L_{s2} x_3 + c_1^2 L_{s2}(V_{sd} - V_{rd}) + \frac{2d^2 C_{dc}}{R_{dc}} x_3\right)$$

$$L_{g4} L_f h(x) = x_5\left(2a_2 c_2 L_{s2} x_4 + c_1^2 L_{s2}\big(V_{sq} - V_{rq}\big) + \frac{2d^2 C_{dc}}{R_{dc}} x_4\right)$$

$$L_f^2 h(x) = \nabla\left(L_f h(x)\right).f(x) =$$

$$\Big[2a_1L_{s1}x_1 - c_1L_{s1}V_{sd},\ \ 2a_1L_{s1}x_2 - c_1L_{s1}V_{sq},\ \ 2a_2L_{s2}x_3 + c_2L_{s2}(V_{sd} - V_{rd}),\ \ 2a_2L_{s2}x_4 + c_2L_{s2}\left(V_{sq} - V_{rq}\right), -\frac{d.C_{dc}}{R_{dc}}x_5\Big] . \begin{bmatrix} 2a_1L_{s1}x_1 - c_1L_{s1}V_{sd} \\ 2a_1L_{s1}x_2 - c_1L_{s1}V_{sq} \\ 2a_2L_{s2}x_3 + c_2L_{s2}(V_{sd} - V_{rd}) \\ 2a_2L_{s2}x_4 + c_2L_{s2}\left(V_{sq} - V_{rq}\right) \\ -\frac{d.C_{dc}}{R_{dc}}x_5 \end{bmatrix}$$

$$L_{g1}\phi_3(x) = 0 \quad L_{g1}\phi_4(x) = 0 \quad L_{g1}\phi_5(x) = 0$$

$$L_{g2}\phi_3(x) = c_1x_5 \quad L_{g2}\phi_4(x) = 0 \quad L_{g2}\phi_5(x) = 0$$

$$L_{g3}\phi_3(x) = 0 \quad L_{g3}\phi_4(x) = c_2x_5 \quad L_{g3}\phi_5(x) = 0$$

$$L_{g4}\phi_3(x) = 0 \quad L_{g4}\phi_4(x) = 0 \quad L_{g4}\phi_5(x) = c_2x_5$$

8.2. System parameters

Parameters of multi machine IEEE system are given in Table 1.

Table 1

Parameters of the machines [9]

Number of generator	**1**	**2**	**3**
P_n (MVA)	247.5	192	128
V_n(kV)	16.5	18	13.8
Power factor	1	0.85	0.85
ω_m (r/min)	180	3600	3600
H	23.64	6.4	3.01
X_d (p.u)	0.1460	0.8985	1.3125
X'_d (p.u)	0.0608	0.1198	0.1813
X_q (p.u)	0.0969	0.8645	1.2578
X'_q (p.u)	0.0969	0.1969	0.25

T_{do} (sec)	8.96	6	5.98
T'_{qo} (sec)	0	0.535	0.6
X_l (p.u)	0.0336	0.0521	0.0742

Reduced admittance matrices in multi-machine system during different conditions are as follow:

- *Pre-fault system:*

$$Y_{R\,pf} = \begin{bmatrix} 0.8455 - 2.9883i & 0.2871 + 1.5129i & 0.2096 + 1.2256i \\ 0.2871 + 1.5129i & 0.4200 - 2.7239 & 0.2133 + 1.0879i \\ 0.2096 + 1.2256i & 0.2133 + 1.0879 & 0.2770 - 2.3681i \end{bmatrix}$$

- *During fault:*

$$Y_{R\,df} = \begin{bmatrix} 0.6568 - 3.8160i & 0 & 0.0701 + 0.6306i \\ 0 & 0 - 5.4855i & 0 \\ 0.0701 + 0.6306i & 0 & 0.1740 - 2.7959i \end{bmatrix}$$

- *Post-fault system:*

$$Y_{R\,af} = \begin{bmatrix} 1.1386 - 2.2966i & 0.1290 + 0.7063i & 0.1824 + 1.0637i \\ 0.1290 + 0.7063i & 0.3745 - 2.0151i & 0.1921 + 1.2067i \\ 0.1824 + 1.0637i & 0.1921 + 1.2067i & 0.2691 - 2.3516i \end{bmatrix}$$

R E F E R E N C E S

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