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Integration of Unified Power Flow Controller with Backup Energy Supply System for Enhancing Power System Stability

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***Abstract*—**An electrical power system has some negative aspects such as flickering and deviations of voltage/power. This can be eliminated using energy storage devices that will provide a backup energy at the time of voltage/power deviations. Energy-storage devices get charging when system voltage/power is higher than reference value and discharging when system voltage/power is lower than reference value, it is acting as catalysts to provide energy boost. In this paper, a dynamic control of Unified Power Flow Controller (UPFC) integrated with superconducting magnetic energy storage (SMES) is developed to improve the power quality, power oscillation damping, and dynamic voltage stability through the transmission line. UPFC inter-connected to SMES through an interface with DC-DC chopper. This inter-connected system is capable of injecting (absorbing) the real and reactive power into (from) the system at the beginning of stability problems. In this paper, the simulation results of UPFC integrated with SMES and UPFC integrated with fuel cells (FCs) are compared using MATLAB/Simulink software package.

***Keywords*—**UPFC, SMES, power system stability, flexible ac transmission systems, fuel cells, chopper.

I. INTRODUCTION

IN practical arrangements, nonlinear networks should not maintain the stable condition due to sudden changes in the load. When there is a load change in the working power system, the system goes for instability situations. This situation needs compensation for maintaining system stability. Nowadays, flexible AC transmission systems (FACTS) are used for power compensating application. The FACTS devices will provide the large amount of power transfer capability in the power network; improve the power quality, power oscillation damping and dynamic voltage stability. UPFC is based on voltage source converter (VSC) controllers; it is one of the second generation FACTS devices which are used to control real and reactive power autonomously as surveyed in [1]-[4]. The existed FACTS component added with energy supply systems is to improve power system stability by active power exchange of power systems. Practical energy supply systems are flywheels, ultra-capacitors, FCs, batteries and SMES. These devices are analyzed on backup voltage supply rates, energy density, lifetime, voltage level, efficiency and economic considerations has been specified in [5].

Electro-chemical battery with STATCOM produced problems like high impedance, higher aging, and high heating levels, and chemical reaction occurring on electrodes. Batteries were able to control high power levels for long time and deep discharges led to high heating levels; obviously reduced battery lifetime was obtained in [6]-[8]. For example, lead acid (flooded type) battery storage system efficiency at 72 to 78%, life span as 1000–2000 cycles at 70% depth of discharge was suggested in [9]. FC is another energy source; however, the life time of the FCs limits its performance on power system networks as acquired in [10]. Electrical energy storage and recovery become ineffective since more energy is consumed in FCs. This is based on different types of FCs [11]. The conversion efficiency of FC is 65 to 70% and overall efficiency of system is equipped with 20 to 40% [12]-[14].

SMES has the advantages as fast response, minimum energy loss, high energy density, high efficiency, etc., so it has been considered as the best substantial energy supply which can be easily integrated with FACTS devices for enhancing transient stability. SMES can also be a good solution to improve the power quality as recommended in the literature [15]-[18].

This paper deals with comparative analysis of UPFC integrated with FC and UPFC integrated with SMES using MATLAB/Simulink software. The proposed system has been tested for IEEE-14 bus system and results are presented. This paper is structured as follows. In Section II, an operation of UPFC and UPFC with SMES model is described in detail. Section III explains integration of UPFC with FC. The results are illustrated with Section IV. Finally, projected systems are concluded with Section V.

II. INTEGRATION OF UPFC WITH SMES

A. Operation of an UPFC

An UPFC unit holds booster transformer and an excitation transformer coupled with back to back VSC1 and VSC2 with common DC link capacitor as shown in Fig. 1. UPFC injects shunt current and series voltage. Independently, it produces/ absorbs reactive power in shunt and series converters since real power can interchange between two converters; consequently, it is working in the range of an angle between -180° and $+180^{\circ}$. The series switching converter is injecting a line voltage by means of controllable magnitude and phase angle. It is taking real power from shunt branch and it is able to absorb/inject both real and reactive power. Shunt switching converter sustains an AC line voltage at its set voltage by providing/absorbing imaginary power from an AC

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transmission network. It holds DC link capacitor voltage based on its set voltage by absorbing active power from an AC line voltage.

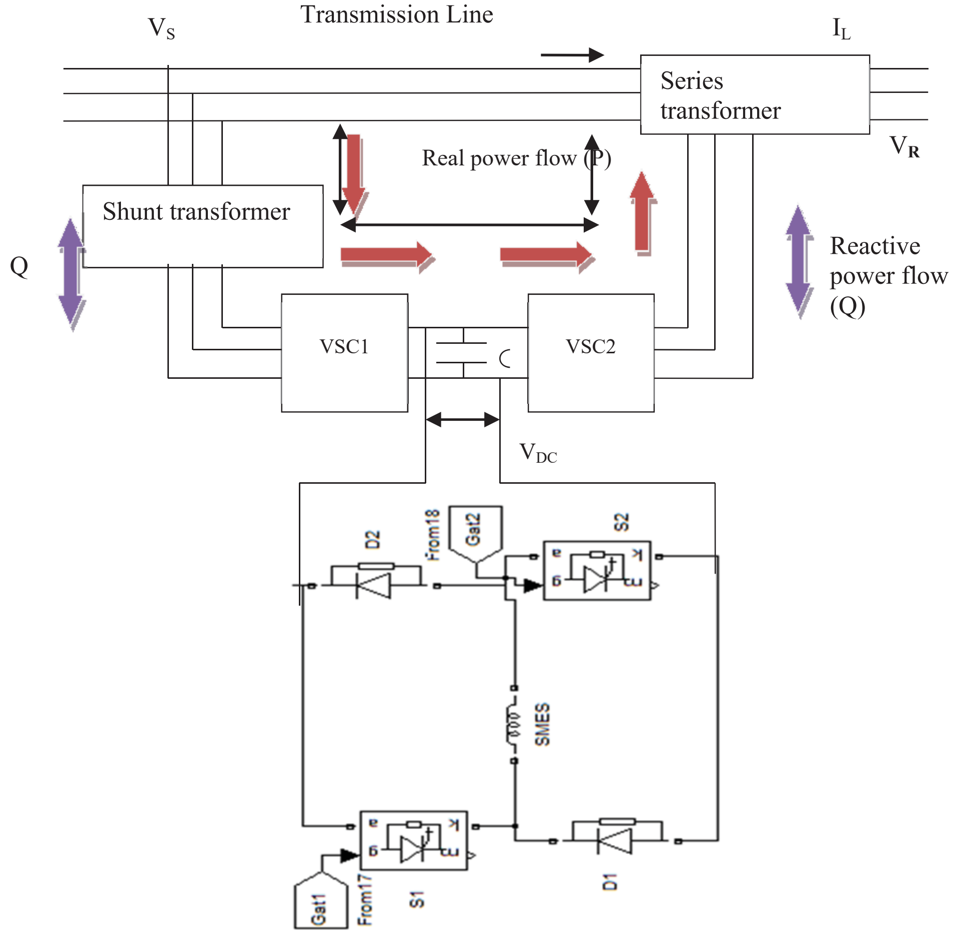

Fig. 1 Operation of an integrated UPFC with SMES

B. Integrated UPFC with SMES

The SMES is an energy storage device which stores energy in a magnetic form. Magnetic energy produced by flowing constant currents through high conductance coils. This device is able to stored magnetic energy and rated power as in (1) and (2) for a long time without any energy leakage. SMES energy storage device is coupled to DC link capacitor of UPFC through a DC-DC chopper showed in Fig. 1. DC bus voltage and current controlled by an interface DC-DC chopper. This control will be accomplished by interpreting the UPFC dc link voltage to an adaptable voltage across the SMES. SMES injects the voltage to DC–bus while dc-bus voltages tend to low compares to set (reference) voltage level. Through chopper SMES absorbs the constant voltage from dc-bus as dc-bus voltages tend to high compare to set voltage level. Energy stored in SMES is

$$E_{SMES} = \frac{1}{2} L_{SMES} I_{SMES}^2 \tag{1}$$

SMES rated power is given by

$$P_{SMES} = \frac{dE_{SMES}}{dt} = L_{SMES} I_{SMES} \frac{dI_{SMES}}{dt} = V_{SMES} I_{SMES} \tag{2}$$

where E_{SMES} is the rated energy of SMES in Wh, L_{SMES} is the inductance of SMES coil in H, I_{SMES} is the current flow in SMES coil in A, P_{SMES} is the rated power for SMES unit in W and V_{SMES} represents voltage across the SMES coil in V.

C. Two Quadrant DC-DC Chopper

Nonlinear power systems need variable backup DC supply for improving system performance. DC-DC chopper used as variable DC source. In DC-DC chopper some different varieties are there such as one quadrant, two quadrants and four quadrants chopper. About these types, two quadrants chopper was used in this paper. Fig. 2 shows two quadrants chopper connected to parallel with DC link capacitor of UPFC.

DC-DC chopper unit has four modes of operation are shown in Fig. 3. Where mode 1 is charging mode of operation, mode 2 is discharging and mode 3 & 4 is standby mode. The first mode of operation is coil charging, when hefty competence of loads is detached from the line. At that time of disconnection large amount of power flow in line, that power was absorbed from the line to storage coils. Since the voltage of the coil (V_{SMES}) is positive as in (3). The relation between V_{SMES} and also the voltage across the dc link capacitor (V_{DC}) are often given as

$$V_{SMES} = D * V_{DC} \tag{3}$$

A second mode of operation is coil discharging when loads are added to the line or after fault clearing time. During the addition of loads, it requires more power injections in line. This injection of extra power is transferred from discharging of the coil to line. Coil voltage is negative as in (4) when the coil is discharging. The relation between V_{SMES} and also V_{DC} are often given as

$$-V_{SMES} = (1 - D) * V_{DC} \tag{4}$$

A third and fourth mode of operation is stored energy in standby mode, when a power system is balanced condition.

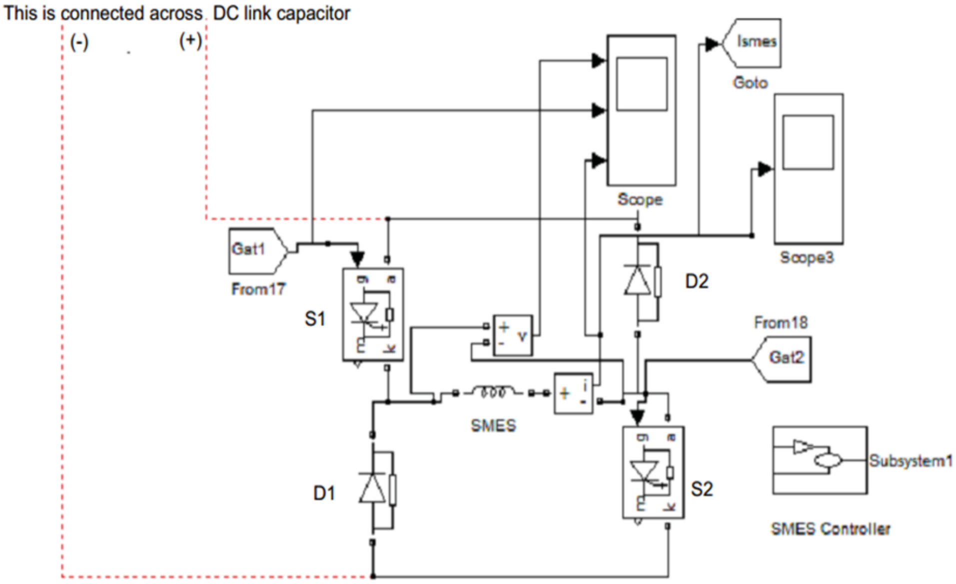

Fig. 2 Chopper circuit Simulink model

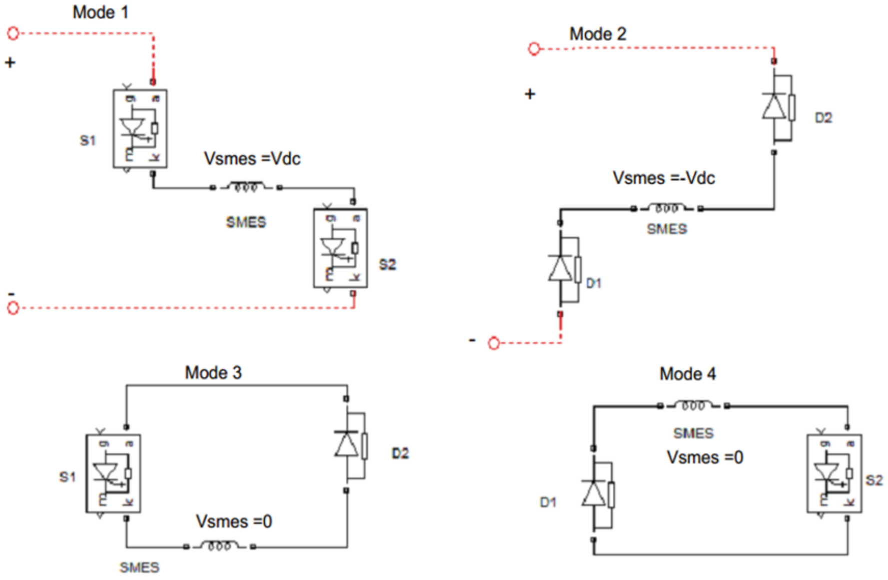

Fig. 3 Simulink for operating modes of DC-DC chopper

III. INTEGRATION OF UPFC WITH FC

A. Fuel Cell

FCs have electrolyte and two electrodes such as anode and cathode, fuel to act as an anode and oxidant act as a cathode. Electricity is produced from the FC with the aid of electrolyte. At an occasion for power generation, ions are stimulated between two electrodes all the way through electrolyte, whereas the result (electricity) and by-product of reaction flow out. The reactant flows should be maintained between anode and cathode for power generation. FCs can generate power from small enormity (1 W) to large scales (multi MW). Miniature capacity of constant current voltage can be generated by a FC. Large amount of voltage is produced by arranging FC in a heap.

FCs allows the dissimilar mixture of fuels and oxidants. Highest energy density fuel is hydrogen, and cathode is oxygen for FC. FC supports some other fuels like alcohols and hydrocarbons, and oxidants such as chlorine dioxide and chlorine. A hydrogen-oxygen FC produces 1.23 V at 298 K at no load condition and it is reduced to 0.5-0.8 V under load conditions. The reaction takes place in hydrogen-oxygen FC is expressed in (5) as,

$$2H_2+O_2 \longrightarrow 2H_2O+\text{electricity}+\text{heat} \tag{5}$$

where H_2 is the hydrogen, O_2 is oxygen and H_2O is water. FCs can be classified according to operating temperature. To implement a generic hydrogen FC model which allows following types of cells for low temperature; Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC). Proton Alkaline Fuel Cell (PAFC) being called intermediate temperature FC. Solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) called as high temperature FC [19]. Cooling and thermal shielding meant for high temperature FCs whereas it does not oblige for low temperature FCs. Power generation, remote power and backup power are applications of FCs.

B. UPFC with FC

FCs connected across DC link capacitor through DC-DC converter in Fig. 4. For the period of any disturbance in power networks, magnitude of voltage/power will be flickered or varied. UPFC capable of compensating tiny voltage variations and it is not sustaining for large voltage variations. Integration of UPFC with FCs used to manage this large voltage/power flickering. The magnitude of UPFC voltage variations described as follows,

The normal condition of a system

$$V_{DC} - V_{ref} = 0 \tag{6}$$

The abnormal condition of a system

$$V_{DC} - V_{ref} < 0 \tag{7}$$

$$V_{DC} - V_{ref} > 0 \tag{8}$$

where V_{DC} is the DC voltage across DC link capacitor and V_{ref} is the reference voltage/ set value. The comparison of DC voltage and reference voltage takes place in above equations. Equation (6) describes the system normal mode, as comparative result produces zero. Comparative result produces a negative value as in (7) means FC supply the voltage to UPFC through DC-DC converter. At the time of positive result described in (8) an extra voltage from UPFC to FC but an extra voltage cannot be stored in FC. This is main drawbacks of UPFC with FC.

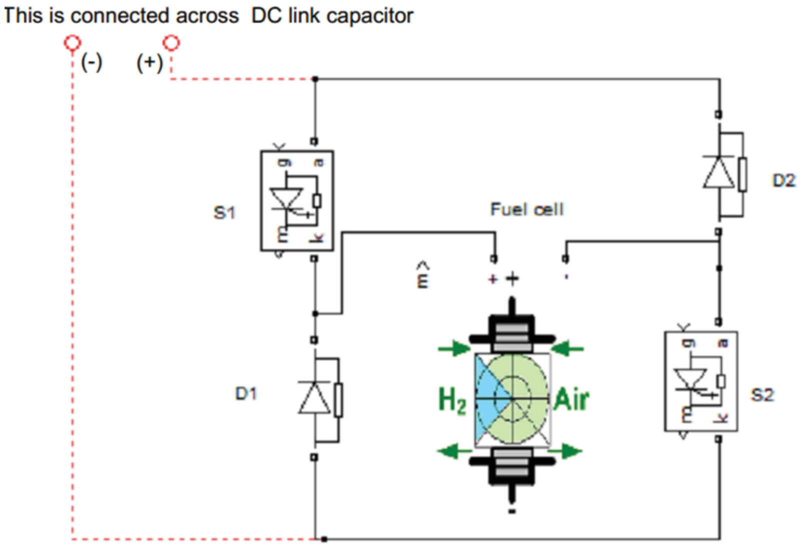

Fig. 4 Operational flow of UPFC with FC

IV. RESULT AND DISCUSSIONS

In order to inspect the possibility of the proposed performance, UPFC-FC and UPFC - SMES power flow analysis carried on IEEE 14-bus test system. Here UPFC-FC and UPFC–SMES had carried out between generator 1 and 2 / bus 1 and 2. In the transmission line a symmetrical fault has been created on the bus at 0.0167s and it is cleared in 0.1s. Result comparisons show for stability improvement and the parameters of given systems are to mentions below. (Given data in pu).

Generator parameters: 100MVA, V =230KV, f = 60 Hz, X_d= 1.305, X_d^1= 0.296, X_d''= 0.255, X_q = 0.474, X_q'' = 0.243, X_l = 0.18, X/R=15.

Shunt and series Transformer parameter: 100MVA 230 kV/38 kV, R_1=0.002, L_1=.08, R_2 = 0.002, L_2 = 0.08, R_m = 500, X_m = 500.

Line parameters and Nominal π network parameter (per km): R_1 = 0.01273, R_0 = 0.3864, L_1 = 0.9337 mH, L_0 = 4.1263 mH, C_1 = 12.74 nF, C_0 = 7.751 nF, L=500 km.

UPFC parameters: 500 KV, 100MVAR, V_{dc} = 38KV, C_{dc} = 2000e^{-6}F, V_{ref} = 1.0, K_p = 12, K_i = 40.

Receiving end source (infinite bus): 100MVA, V =230KV, f = 60 Hz, X/R=7, L = 1e-3H, R = 0.15.

Figs. 5 and 6 represents DC bus voltage of UPFC-FC and UPFC-SMES respectively, here system fault cleared in 0.1s. UPFC-SMES system was settled at the time of 0.12s whereas UPFC-FC system achieved stability at 0.16s.

Figs. 7 and 8 comparison of real and reactive power at sending end has been carried out. Here negative value corresponds to inject real and/or reactive power to AC system from the compensating unit.

An evaluation of real and reactive power at receiving end is shown in Figs. 9 and 10. Real and reactive power takes a few seconds to stable state at post fault clearing. Real and reactive power of UPFC-FC is settled after 0.3s and it produces an oscillation throughout the operation, while UPFC-SMES gets settled before 0.3s and its retaining constant.

An AC voltage of power systems was compared with Figs. 11 and 12. Post faults clearing UPFC-SMES based systems had better performance. From simulation results, performance was evaluated on various parameters such as DC Voltage (Vdc), real (P) and reactive (Q) power for UPFC-FC and UPFC-SMES. In UPFC-FC based system, FC supplies an active power flow path for UPFC; however, UPFC controller is independent of backup supply. Inferred from the results SMES absorbs/injects a real power flow path to UPFC. Here stability of power systems with UPFC-SMES is faster than UPFC-FC.

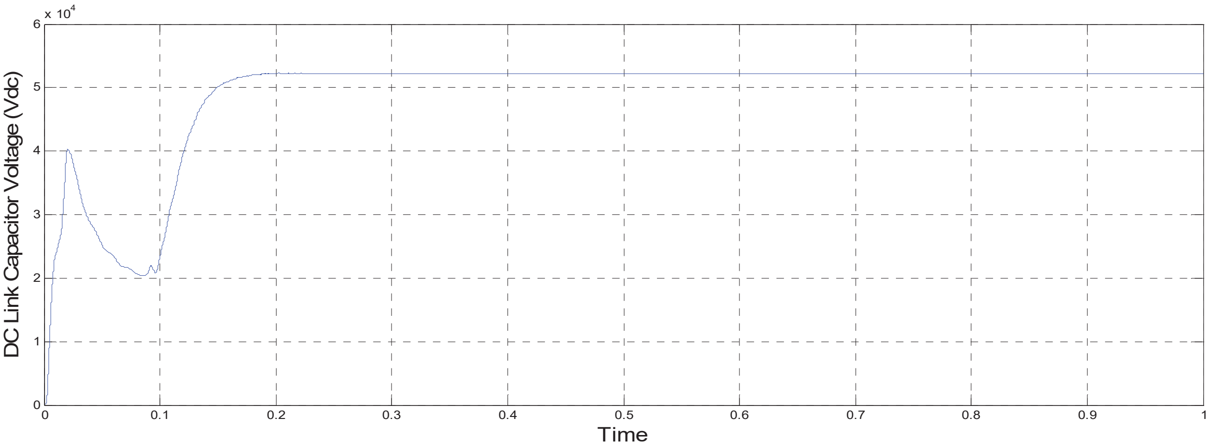

Fig. 5 DC bus voltage for UPFC-FC

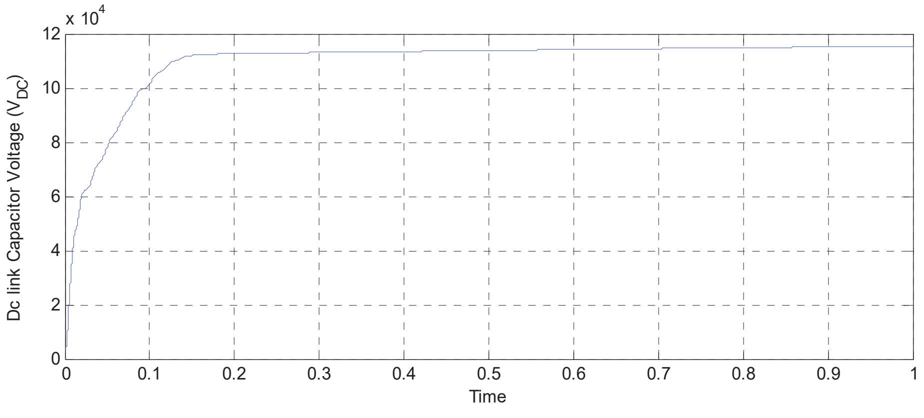

Fig. 6 DC bus voltage for UPFC-SMES

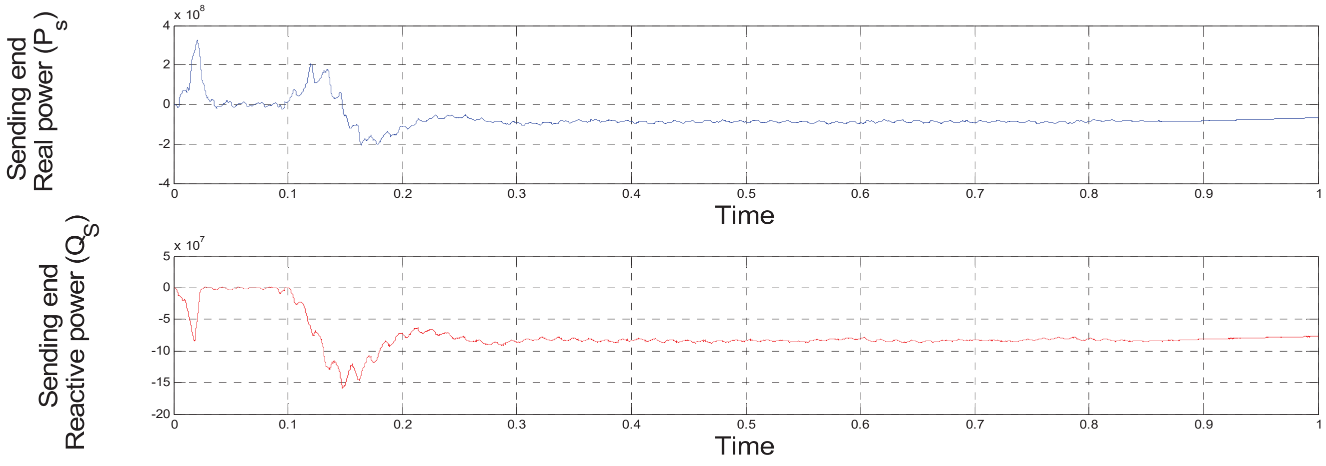

Fig. 7 Transmission line powers at Sending end for UPFC-FC

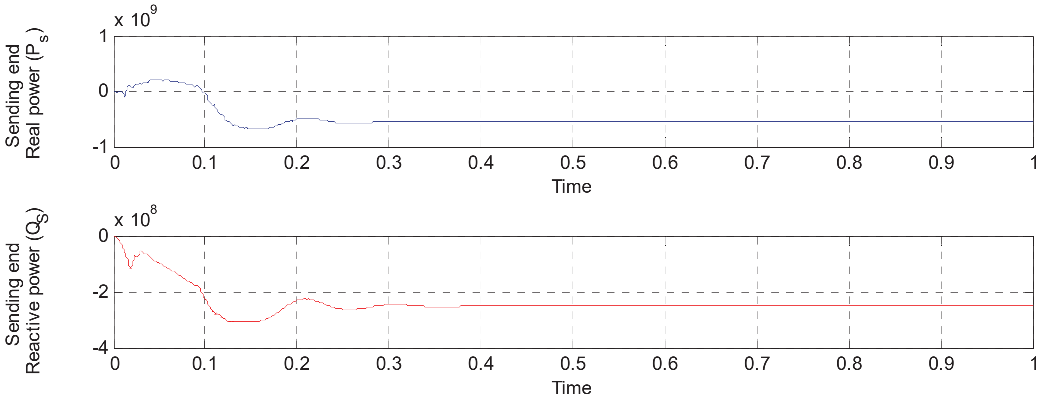

Fig. 8 Transmission line powers at sending end for UPFC-SMES

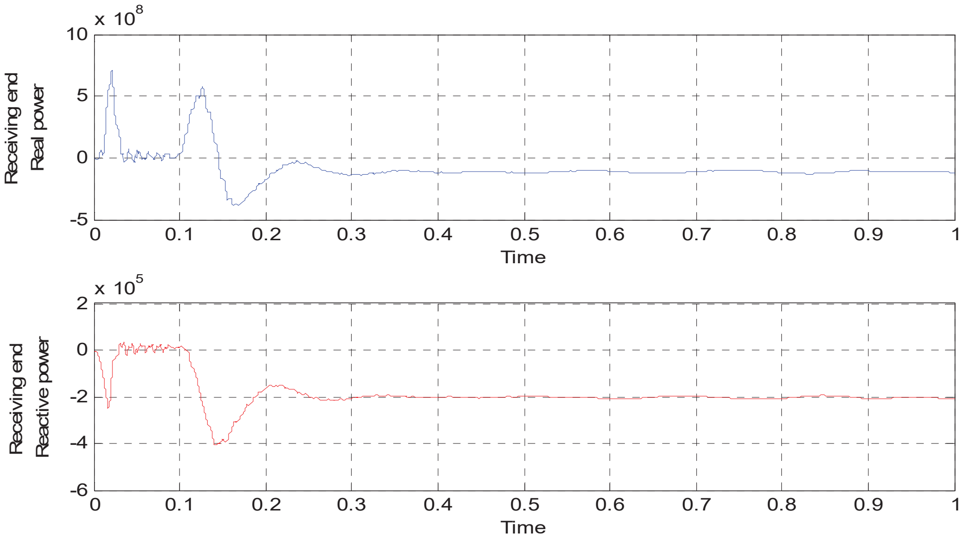

Fig. 9 Transmission line powers at receiving end for UPFC-FC

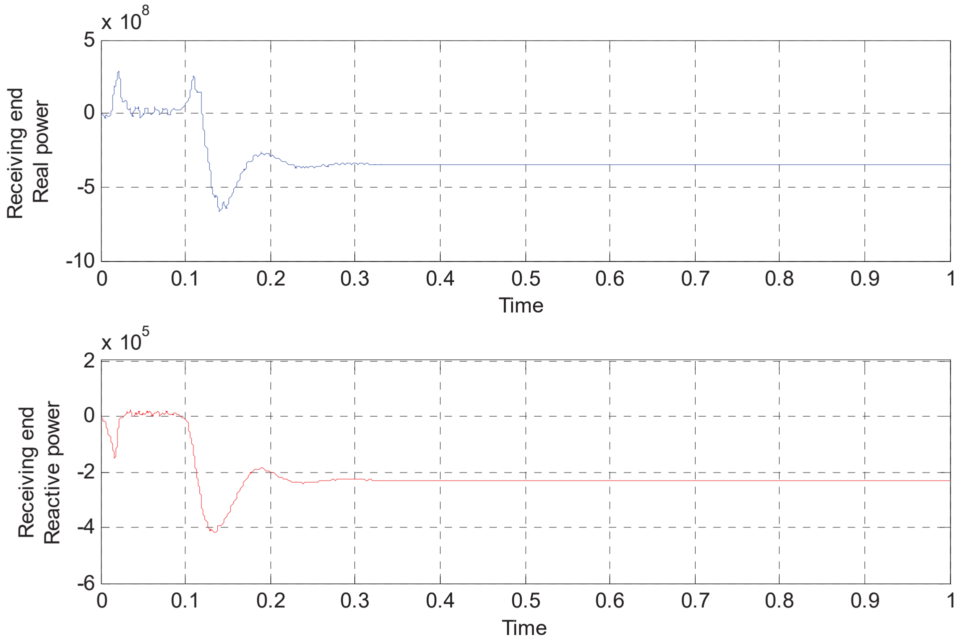

Fig. 10 Transmission line powers at receiving end for UPFC-SMES

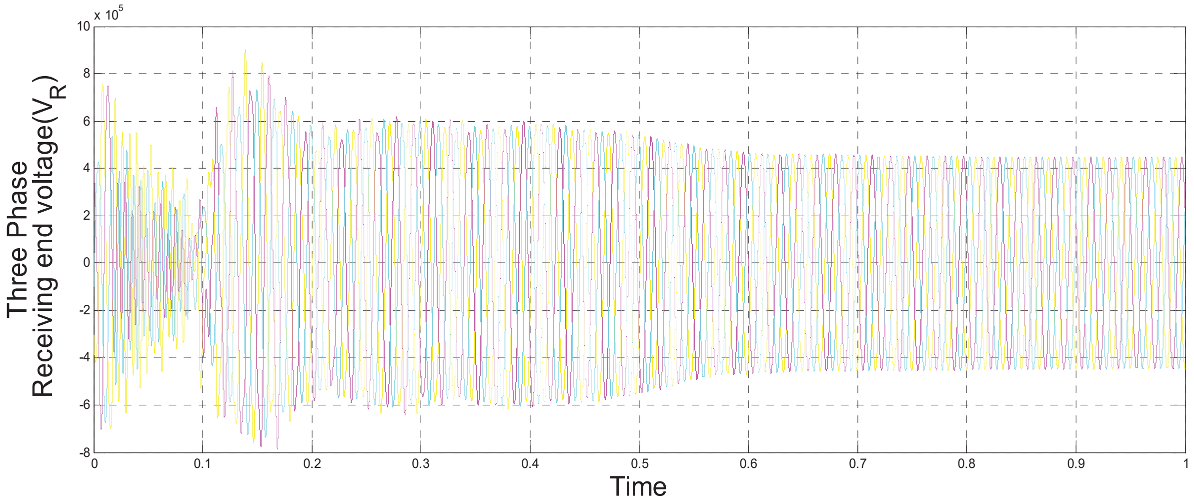

Fig. 11 Three phase receiving end voltage for UPFC-FC

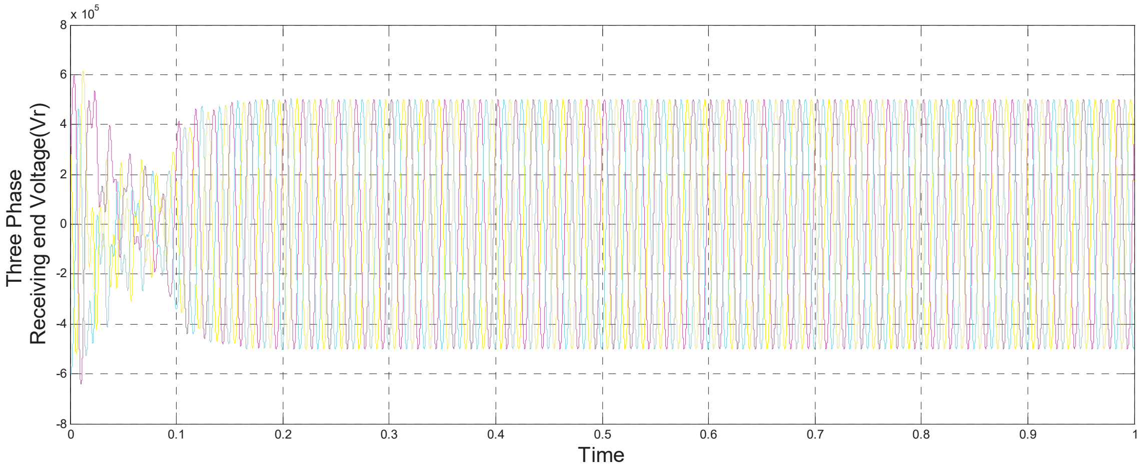

Fig. 12 Three phase receiving end voltage for UPFC-SMES

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V. CONCLUSION

This research deals with the stability analyses using backup energy supply systems like UPFC-FC and UPFC-SMES. An analysis carried out by MATLAB/Simulink model and their dynamic responses are presented. The proposed system illustrated that to preserve constant voltage across the dc-link capacitor of UPFC, its required voltage to be absorbed from the SMES. Based on dc bus voltage, an UPFC terminal voltage retains controllability at post fault condition. In short duration of timing the SMES system is competent of charging/discharging huge amount of energy consequently serving for dynamic performance. The results inferred that UPFC-SMES combination is very efficient than UPFC-FC combination system for stability enhancement in the power transmission network level. An UPFC conjunction with SMES is concluded as a suitable approach for an oscillation damping and higher compensation of power systems.

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