Design Coordination of a Fuzzy-based Unified Power Flow Controller with Hybrid Energy Storage for Enriching Power System Dynamics

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ABSTRACT

In power networks, operation planning has become necessary due to the continuously increased load demand. The Unified Power Flow Controller (UPFC) controls the power flow through the network and improves the dynamics of the power system. In this paper, the design application of the coordination of a fuzzy-based UPFC with hybrid energy storage has been proposed to enrich the system's dynamic performance during abnormal conditions and improve the hybrid energy storage performance during transients when the DC link voltage is insufficient to meet the converter voltage demand. The hybrid energy storage consists of a supercapacitor and a battery connected across the UPFC Vdc shunt capacitor. The proposed system to improve the UPFC performance during large disturbances on a multi-machine system was designed and tested in MATLAB/SIMULINK.

Keywords-fuzzy logic; UPFC; hybrid energy storage; super capacitor; battery; dynamic stability

I. INTRODUCTION

In modern power networks, the interconnected transmissions have to limit the challenges on stability, security, and control operation of the power system in order to operate the transmission network below its thermal capability. When transferring power at a high voltage level, a power system's transient stability refers to its capacity to keep equipment running synchronously in the face of significant disturbances [1]. Flexible AC Transmission System (FACTS) controllers are utilized in power transmission systems to increase the stability of the electrical network. The most adaptable FACTS device is the UPFC. The UPFC's main duty is to regulate the flow of both reactive and actual power by providing a voltage to the line. Voltage control, improved transient stability and damping oscillation are the secondary functions of the UPFC [2]. In the UPFC design, the shunt converter's primary job is to generate or absorb active power from the line, much like a shunt compensator. The DC link capacitor can be charged by the shunt converter, which also uses it to power the series converter. Any losses and useful power utilized or supplied by the series branch must be compensated by a shunt branch. If the power balance is not maintained, voltage cannot remain constant. The active power can have a closed channel via the converter but the reactive power cannot due to the associated DC link capacitor between the two converters. During small transients, the DC bus compensates for the converter losses in the UPFC by charging or discharging operations [3]. The energy in the DC bus cannot be suppressed during large transient oscillations without degrading the DC voltage. In order to reduce oscillations without impacting the effect of DC link voltage, it is desirable to interchange real power with the storage device when using a fully discharged hybrid energy storage system with a back to back DC-DC converter [4-5]. To offer a significant amount of short-term actual power exchange, a shunt with a DC bus capacitor and a hybrid energy storage device are used. The components of a UPFC with hybrid energy storage are coordinated by using fuzzy logic to improve the transient stability of the system. Authors in [1] introduce the pole-shifting controller-based CSC-STATCOM, which is intended to improve the transient stability of a two-area network. In order to boost oscillation damping capabilities, a damping stabilizer based on PSS is being used. However, they are unable to confirm how well the fuzzy-based UPFC with hybrid energy storage will operate in a dynamic environment. The way a coordinated UPFC based on fuzzy logic affects the flow of actual power was evaluated in both normal and abnormal circumstances in [2]. The performance of the hybrid energy storage is not a metric in this case. The STATCOM can be used along with battery energy storage with the performance indices technique for improved power situation when using various power controllers [3]. Due to the additional control freedom, the FACTS/BESS has greater flexibility and damping capabilities than the standard FACTS. However, the use of fuzzy-based hybrid energy storage in conjunction with the UPFC for dynamic performance was not tried. Authors in [4] offer a new approach of decreasing the error by the coupling of a neuro-fuzzy scheme with the PI controller for boosting transient stability. However, the damping capability of the hybrid energy storage was not tested. The first swing stability problem is dampened by the UPFC utilizing a local measurement approach. The use of hybrid energy storage in conjunction with the fuzzy-based UPFC to maintain the necessary DC bus voltage to transfer real power across converters during an interruption was not demonstrated [5]. Authors in [6] present an innovative, best-practice fuzzy PID controller based on UPFC, its gains are increased when the time-weighted absolute error integral is taken into consideration by the PSO-GWO method. Low frequency oscillations in the power system have been reduced with the proposed controller, but the impact of storage with UPFC was not covered. In [2], a fuzzy logic technique was used to increase a power network's transient stability. The unified power flow controller has three synchronized control inputs. However, how well the fuzzy-based UPFC works with storage hasn't been tested. Authors in [7] examined quadrature voltage control and in-phase voltage control as fuzzy logic-based UPFC solutions for enhancing power system transient stability utilizing the energy function method. However, the compatibility of fuzzy-based UPFC with storage was not examined. In order to improve the transient stability for UPFC, the authors in [8] looked towards designing a neuro-fuzzy controller, although the fuzzy-based UPFC with storage was not investigated. For improving transient stability, RBFN-based UPFC performance was reported in [9], but UPFC with storage was not considered. For improving transient stability, RBFN Based UPFC Performance was reported in [10]. Many researchers presented combinations of fuzzy-based UPFCs [11-13]. However, they did not focus on the effects of the hybrid energy storage during abnormal conditions [14-16]. The above mentioned authors did not covered in depth the hybrid energy storage, which consists of a supercapacitor with lithium-ion batteries connected across the Vdc of the UPFC, during large sudden disturbances in a power network. Hybrid energy enhances the UPFC primary function of power flow and the secondary function of oscillation damping. The PI-based UPFC has limitations under various system conditions in large nonlinear systems. The fuzzy-based UPFC replaced the PI with significant improvement of performance.

In this study, we present the design of a fuzzy inference for series and shunt Voltage Source Converter (VSC)-based UPFC controller to improve the transient performance of UPFC, which is comparable with the PI-based UPFC. The transient performance of the UPFC was enhanced during sudden large disturbances in the power network by connecting hybrid storage across Vdc. According to the simulation results, the coordination of the fuzzy-based UPFC combined with the hybrid energy storage will function better in enhancing the dynamics under significant disturbances in the network. The improved UPFC performance has led to an improvement in system performance. MATLAB was used to test the proposed fuzzy-based UPFC design with hybrid energy storage in a multi-machine scenario.

II. THE PROPOSED MODEL

The power network used in this paper is a multi-machine system with UPFC in combination with hybrid energy storage during abnormal condition as shown in Figure 1. Generator G1 represents dynamic sources, while Generators G2 and G3 provide static sources. Two six-pulse converters linked to a common capacitor make up the power injection model of the UPFC. The UPFC shunt converter regulates the useful power insertion from the shunt converter to the power network by controlling the DC bus voltage across the capacitor. In contrast, a VSC that is connected in series can inject a voltage at the line frequency that has a controlled magnitude and phase angle. As a result, the VSC connected in series receives a very less amount of useful power from the transmission system to change the injected series voltage. A back-to-back dc-dc converter is used to create a shunt connection between the DC bus of the UPFC device and the hybrid energy storage, as shown in Figure 1. In order to enhance the dynamic stability of the power network, the UPFC device often generates or absorbs reactive power. When the DC bus capacitor is unable to support the UPFC during a transient circumstance, the hybrid energy storage offers its energy storage to the UPFC [17, 18]. The converters' ability to exchange real power is required anytime. When there are disturbances, it can maintain a balance in the power transmission between generation and demand without violating the stability limit. While the UPFC-hybrid energy storage is connected between bus B1 and B2, a 3-phase short circuit fault occurs near bus B1 for durations of 0.3s and 0.2s.

The following equation describes the generator dynamics:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \tag{1}$$

where *Pm* is turbine power, *Pe* is output electrical power, *M* is the inertia constant, and δ is the torque angle.

The fundamental *P* and *Q* equations are:

$$P = \frac{V_t E_f}{X_d}\sin\delta + \frac{V_t^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta \tag{2}$$

$$Q = \frac{E_f V_t}{X_d}\cos\delta + V_t^2\left[\frac{1}{X_q} - \frac{1}{X_d}\right] sin^2\delta - \frac{V_t^2}{X_d} \tag{3}$$

The UPFC equations are:

$$P = \frac{V_i V_j}{\mathrm{X}}\sin\delta + \frac{V_{se} V_j}{\mathrm{X}}\sin(\delta + \rho) \tag{4}$$

$$Q = \frac{V_i V_j}{\mathrm{X}}(\cos\delta - 1) + \frac{V_{se} V_j}{\mathrm{X}}\cos(\delta + \rho) \tag{5}$$

when $\rho = 90^0 - \delta$.

The hybrid energy storage consisting of a super capacitor and a battery is demonstrated in Figure 2.

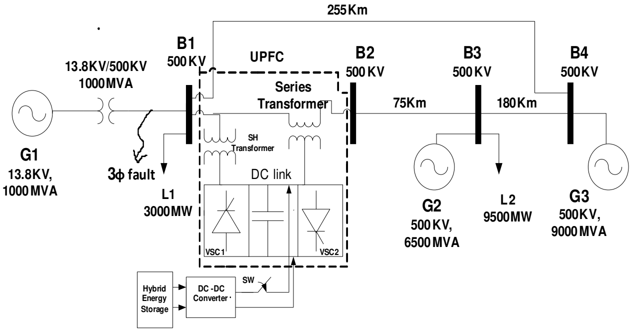

Fig. 1. System model with combination of UPFC and hybrid energy storage.

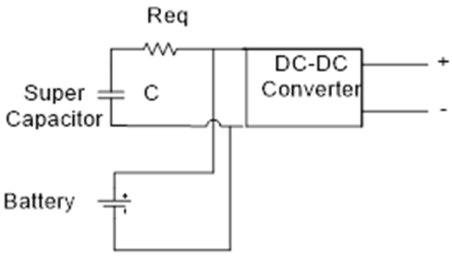

Fig. 2. Hybrid energy storage.

The supercapacitor output voltage is expressed as:

$$V_{SC} = \frac{N_s Q_T d}{N_p N_e \epsilon \epsilon_0 A_i} + \frac{2 N_e N_s R T}{F} \sinh^{-1}\left(\frac{Q_T}{N_p N_e^2 A_i \sqrt{8RT\epsilon\epsilon_0 c}}\right) - R_{SC} \cdot i_{SC} \quad (6)$$

where Q_T is the electric charge, N_s is the number of series supercapacitors, N_p the number of parallel supercapacitors, R the ideal gas constant, T the operating temperature, d the molecular radius, N_e the number of layers of electrodes, A_i the interfacial area between the electrodes and the electrolyte, c the molar concentration, and F the Faraday's constant.

The super capacitor energy is directly proportional to the DC voltage and its capacitance is [17]:

$$E_{SC} = \frac{1}{2} C V_{SC}^2 \quad (7)$$

The maximum power of the super capacitor is:

$$P_{max} = \frac{{V_{SC}}^2}{4R_{eq}} \quad (8)$$

where R_{eq} is the equivalent resistance.

The stored energy in a battery depends on the stored charge and its voltage. The operating power of a battery is represented by:

$$P = VI = (E-IR)\,I = EI - I2R \quad (9)$$

The following equations are used in the lithium-ion battery model:

a) Model for Discharge $(i^* > 0)$

$$f_1(it, i*, i) = Eo - K.\frac{Q}{Q-it}\,.\,i* - K.\frac{Q}{Q-it}\,.\,it + A.exp(-B.it) \quad (10)$$

b) Model for Charge $(i^* < 0)$

$$f_2(it, i*, i) = Eo - K.\frac{Q}{it+0.1Q}\,.\,i* - K.\frac{Q}{Q-it}\,.\,it + A.exp(-B.it) \quad (11)$$

where A is the exponential voltage, B is the exponential capacity, E_0 is the constant voltage, K is the polarization constant, i^* is the low-frequency current dynamics, i is the battery current, and Q is the maximum battery capacity.

The hybrid energy storage voltage and the steady state DC bus voltage are related through the duty cycle D, which can be modified in such a way that it will helps damp power oscillations as:

$$V_{dc} = \frac{D}{1-D} V_{HES} \quad (12)$$

A. Fuzzy Logic-based UPFC

In comparison to the traditional control strategy, the advantage of the fuzzy logic technique is that it does not need exact quantitative values for the control inputs and system variables. Fuzzy logic controllers are more adaptable and work without the need for a mathematical description of the power network. The fuzzy logic approach is a good and effective method for regulating a UPFC.

B. Fuzzy-based Shunt Voltage Regulator of the VSC

The input to the fuzzy logic controller consists of *Vref* and *Vmes*. The process of fuzzification entails mapping the input variables onto linguistically fuzzy variables. There is a distinct membership function for each fuzzy variable. The inputs are fuzzy-set using 3 trapezoid-shaped membership functions. The voltage regulator is achieved by adjusting the difference of *Vref* and *Vmes* which is the input to the fuzzy logic as shown in Figure 3. On the basis of fuzzed linguistic features, control judgments are made. Inference entails guidelines for selecting which outputs to employ. The input variables of the fuzzy coordination controller of the shunt voltage regulator consist of 3 fuzzy variables and 9 fuzzy rules to control the shunt current.

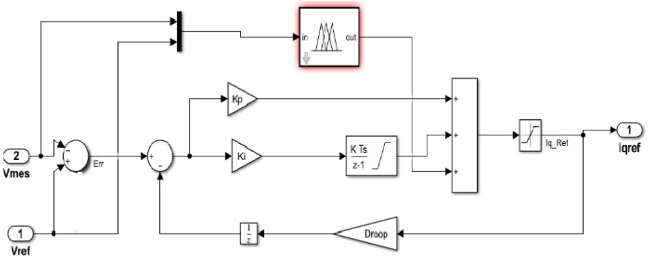

Fig. 3. Fuzzy-based shunt voltage regulator of VSC.

Table I shows the input output mapping of the fuzzy rule-based system. The Mamdani inference system produces linguistic variables as its output. They need to be quantitatively translated into the output. The fuzzy controller employs the centroid approach.

C. Fuzzy-based Series Current Regulator of the VSC

Using a current regulator, the line currents are forced to match the corresponding reference values in order to control the useful and reactive power flow in the line. Each fuzzy variable has a different membership function. For input and output, trapezoidal membership functions were chosen. As shown in Figure 4, the fuzzy control produces the series injected voltage in collaboration with 2 separate PI controllers. A collection of basic membership functions is produced using the current. Nine concepts are used by the fuzzy coordination controller to control series voltage. A time-based pulse in a model of all-systems has a defuzzifier as its final state.

TABLE I. INPUT-OUTPUT MAPPING OF THE SHUNT VSC

Vm ***V ref***	***S_Vm***	***M_Vm***	***L_Vm***
S_V ref	*S_O/P*	*M_O/P*	*L_O/P*
M_V ref	*M_O/P*	*M_O/P*	*L_O/P*
L_V ref	*L_O/P*	*L_O/P*	*L_O/P*

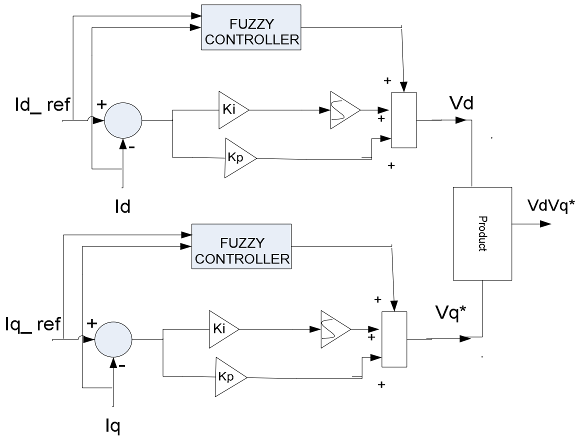

Fig. 4. Series current regulator of VSC with fuzzy logic.

The design of the series current regulator for the fuzzy inference system of the VSC is shown in Tables II and III.

TABLE II. SERIES CURRENT REGULATOR SIGNAL ID INFERENCE SYSTEM COORDINATION FOR VSC

Id **Id ref**	**S_Id**	**M_Id**	**L_Id**
S_Idref	S_O/P	M_O/P	L_O/P
M_Idref	M_O/P	M_O/P	L_O/P
L_Idref	L_O/P	L_O/P	L_O/P

TABLE III. COORDINATED SERIES CURRENT REGULATOR SIGNAL IQ OF THE VSC INFERENCE SYSTEM

Iq **Iq ref**	**S_Iq**	**M_Iq**	**L_Iq**
S_Iq ref	S_O/P	M_O/P	L_O/P
M_Iq ref	M_O/P	M_O/P	L_O/P
L_Iq ref	L_O/P	L_O/P	L_O/P

III. SIMULATION RESULTS

The digital simulation of the hybrid energy storage with fuzzy logic-based UPFC was carried out in a multi-machine system in MATLAB when a 3-phase fault occurs at the sending end of the transmission lines near bus B1. The aim is to enhance the power system dynamic performance as well as to check the secondary function of UPFC to damp out the oscillations during abnormal conditions. The design coordinated action of the fuzzy-based UPFC with hybrid energy storage improves the damping performance of the system and reduces the dynamics.

Figure 5 demonstrates how the fuzzy-based UPFC with hybrid energy storage reduces the power fluctuations in the rotor speed of the generator G1 in all the considered scenarios during fault durations. The system with the fuzzy-based UPFC and the hybrid energy storage is superior than without UPFC, with PI-UPFC, and with fuzzy logic-based UPFC. It significantly improves the dynamic performance of the system. The proposed fuzzy-based UPFC with hybrid energy storage was tested in a multi-machine system for fault durations of 0.2 and 0.3s. The terminal voltage of the generator G1 is shown in Figure 6. The results indicate that the proposed fuzzy controller has satisfactory operation over the PI-based controller and gets better enrichment in the dynamic performance of the system. The fuzzy-based UPFC with hybrid energy storage stables the generator G1 terminal voltage waveform in minimum number of cycles.

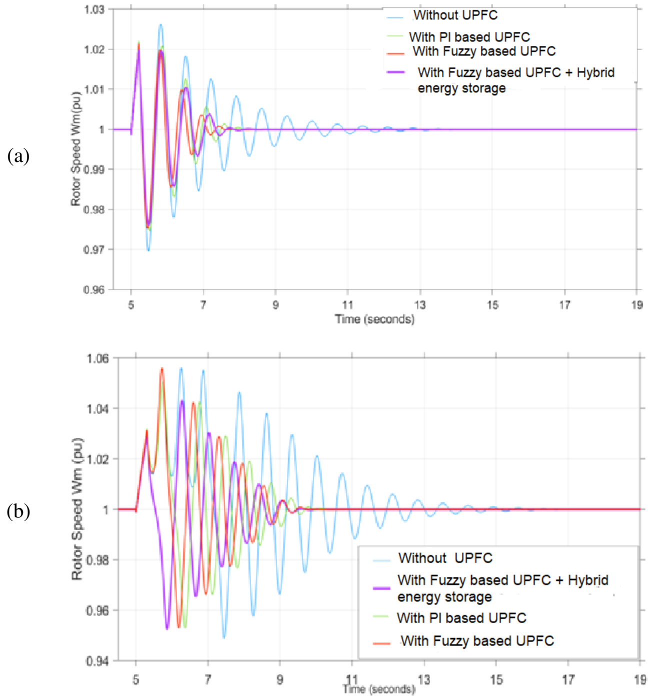

Fig. 5. Speed of rotor at G1 without UPFC, with UPFC based on PI, with fuzzy logic-based UPFC, and with fuzzy logic-based UPFC and hybrid energy storage during (a) a 0.2s fault and (b) a 0.3s fault.

Figure 7 shows that the initial swing is suppressed under post fault conditions. The flow of real power with the fuzzy-based UPFC with hybrid energy storage indicates that it increases the power handling capability of the UPFC during transient conditions when the DC link capacitor is inadequate to exchange the real power between the converters.

Figure 8 indicates that the fuzzy-based UPFC with hybrid energy storage provides reactive power support during large disturbances to maintain the DC link voltage between the converters and also helps maintain voltage profile after clearing the fault.

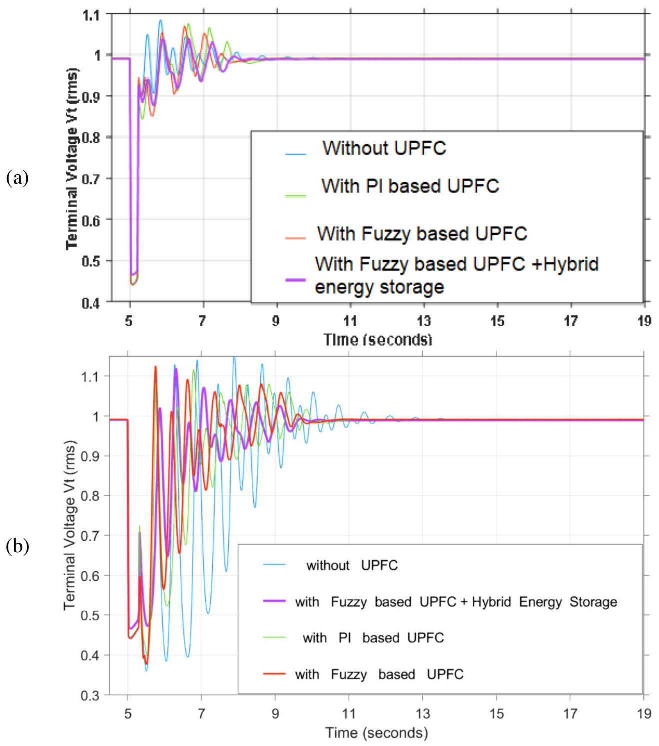

Fig. 6. G1 terminal voltage without UPFC, with UPFC based on PI, with fuzzy logic-based UPFC, and with fuzzy logic-based UPFC and hybrid energy storage during (a) a 0.2s fault and (b) a 0.3s fault.

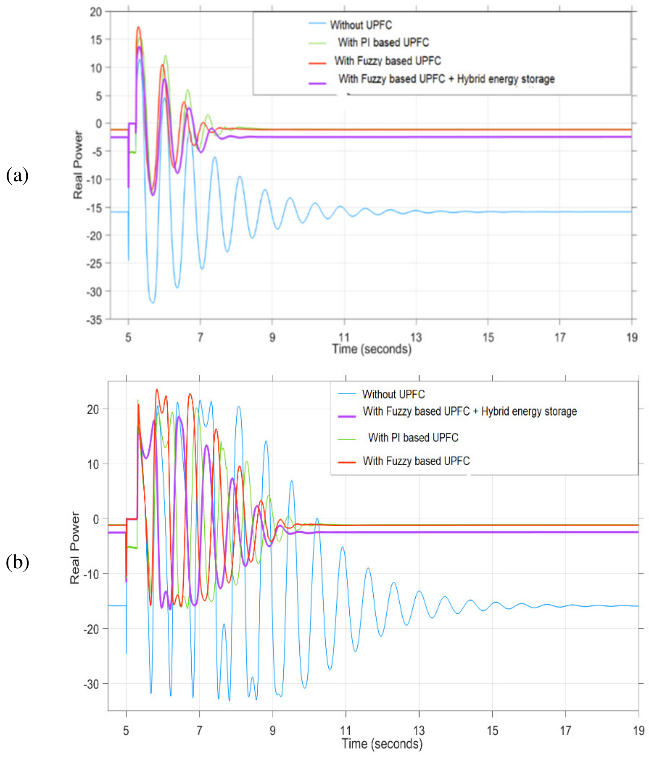

Fig. 7. Bus B2 real power voltage without UPFC, with UPFC based on PI, with fuzzy logic-based UPFC, and with fuzzy logic-based UPFC and hybrid energy storage during (a) a 0.2s fault and (b) a 0.3s fault

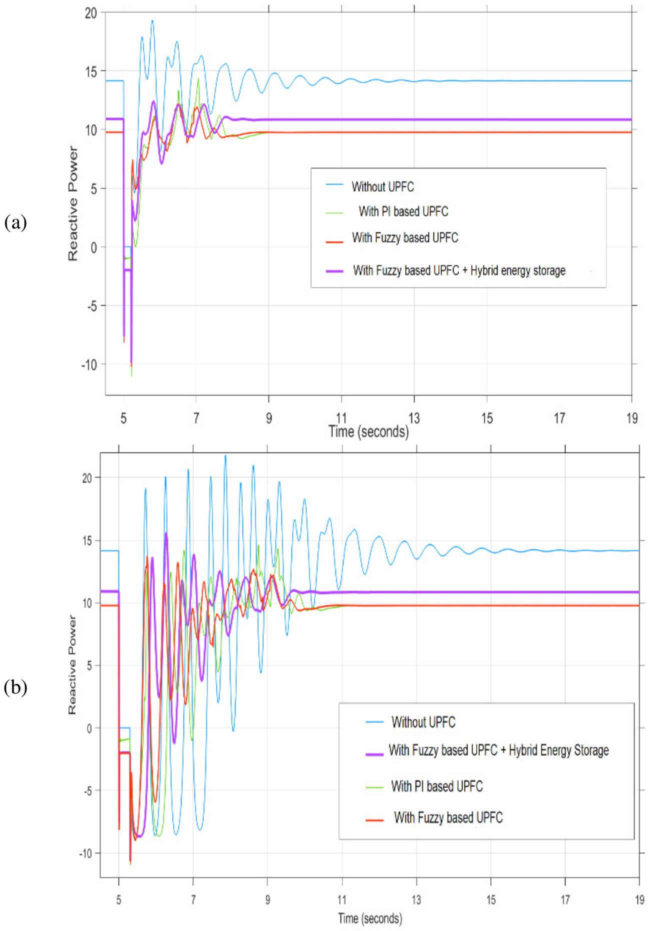

Fig. 8. Bus B2 reactive power voltage without UPFC, with UPFC based on PI, with fuzzy logic-based UPFC, and with fuzzy logic-based UPFC and hybrid energy storage during (a) a 0.2s fault and (b) a 0.3s fault

IV. DISCUSSION

Rotor speed damping varies from 13s without UPFC to 7.5s with the fuzzy-based UPFC with hybrid energy storage for the fault duration of 0.2s. Therefore, settling time reduces by 42.3%. Similarly, for 0.3s fault duration, the settling time of the rotor speed without UPFC is 9.5s which reduces to 5.5s with the fuzzy-based UPFC with hybrid energy storage (38.7% reduction). These values indicate the significant dynamic performance of the fuzzy-based UPFC with hybrid energy storage for improving the dynamic stability of the system. The primary function of the UPFC is to regulate the terminal voltage which is enhanced by the fuzzy-based UPFC with hybrid energy storage. The basic function of the UPFC is to control real and reactive power under abnormal condition, something that has been significantly achieved with the proposed controller. The proposed hybrid energy storage with UPFC improves the fundamental performance of the UPFC during sudden large disturbances hence the system dynamic stability is improved.

V. CONCLUSION

In this paper, a fuzzy-based UPFC with hybrid energy storage is proposed to enrich the power system dynamics. The design objectives are to maximize the power flow and to minimize the oscillation damping during large disturbances in a multi-machine system. The simulation results illustrate that the combination of the fuzzy-based UPFC with the hybrid energy storage meets the design objectives and demonstrate the robustness of the fuzzy logic controller over the PI controller. Due to the hybrid energy storage application during large disturbances with duration of 0.2s and 0.3s, the real power support from *Vdc* to the system increases and helps oscillation damping. The fuzzy inference is designed to coordinate the PI controller with the storage device. The overall performance of the UPFC during disturbance conditions has been significantly improved.

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