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Intelligent Coordinated Control of a Wind Farm and Distributed SmartParks

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***Abstract* -- Energy storage is generally recommended in presence of an intermittent source like wind farm for a better control over the power generation from the wind turbine with the variation of the wind speed. In this paper, the potential of plug-in electric vehicle parking lot (SmartPark) as an energy storage in a power system with a large wind farm has been investigated. Also, a fuzzy logic based coordination controller of the wind farm and the distributed SmartParks has been proposed in this paper. The fuzzy controller uses the total state-of-charge of the SmartParks and the difference between instantaneous demand and the available wind power generation as the inputs and thereby generates the charging or discharging power commands of the SmartParks and the pitch angle reference for the wind turbine. A 12-bus multimachine power system with a 400 MW wind farm is used as a test system. Six SmartParks are also connected to the same bus where the wind farm is connected. The entire model is developed in Real-Time Digital Simulator (RTDS) for power system. The results demonstrate the action of the coordinated controller to reduce the oscillations in the tie-line power flow with the sudden variations of the wind speed.**

***Index Terms*-- energy storage; fuzzy logic controller; plug-in electric vehicles; SmartParks; wind farm**

I. INTRODUCTION

The penetration of renewable sources of energy is increasing rapidly all over the world. Among various sources, the growth of wind power has superseded the others especially in Europe and United States [1]. The main disadvantage of wind power is its intermittent nature. The power generated from wind farm varies with the wind speed. If the wind speed is low, generally the maximum possible power is extracted from the wind turbine corresponding to that wind speed. If the wind speed is high, the pitch control is active to limit the power generated from the wind turbine. Now, if the wind farm is connected to the grid, this kind of fluctuation in generated power from the wind farm may cause stability problems in the system. One way to solve this problem is to use additional energy storage device. Generally the energy storage devices like batteries or ultracapacitors are connected to the dc link in between the rotor side and grid side inverters of the Doubly Fed Induction Generator (DFIG) through a dc-dc converter [2]. With this energy storage, a better control over the power generated by the wind farm can be achieved. But, if the wind farm is large and consists of several DFIGs, then each DFIG has to be equipped with one energy storage device and one additional dc-dc converter. This will increase the cost and also require a more complex control strategy.

As an alternative approach to solve this problem, the use of plug-in vehicle parking lots (SmartParks) for energy storage is proposed. The number of plug-in electric vehicles (PEVs) entering into the market is increasing and many of these vehicles are supposed to participate in vehicle-to-grid (V2G) power transactions in the proposed smart grid infrastructure, where bidirectional power flow between the vehicle and the grid will become very obvious [3-4]. In that scenario, it is quite reasonable to assume that the plug-in vehicle parking lots or the SmartParks can be used as energy storage and with a proper coordination with the wind farm, they can minimize the shock on the system due to the wind gust, reduce the congestion in the transmission lines and also improve the stability of the system during rapid fluctuations in wind speed.

The coordination of the SmartParks with the wind farm can only be achieved with a proper control strategy. This paper proposes a fuzzy logic based controller which uses the difference between the demand and availability of wind power and the overall state-of-charge of the SmartParks as inputs and based on some rules, generates the charging or discharging power commands for the SmartParks and the pitch control reference of the wind farm. In this paper, the standard IEEE 12-bus multimachine power system is considered to be the test system, where, one of the hydro units is replaced by a 400 MW wind farm. Six SmartParks are modeled in such a way, that each of them can deliver or absorb 20 MW to or from the grid respectively. These SmartParks are connected to the same bus where the wind farm is connected. The entire model is developed on the Real-Time Digital Simulator (RTDS) platform and the fuzzy controller is implemented on a DSP.

The rest of the paper is organized as follows: Section II describes the overall test system, the modeling and control of the wind farm and the SmartParks. Section III explains the fuzzy logic based coordinated control strategy proposed in this paper. The results and discussions are presented in Section IV. Finally, conclusions and future work are given in

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Section V.

II. MODELING OF TEST SYSTEM

A. Modeling of the overall system

The overall test system including the wind farm and the SmartParks is shown in Fig. 1. The 12-bus system was proposed in [5] to evaluate the effects of FACTS devices in the transmission level. The system has four generators and three interconnected areas. Generator G1 represents the infinite bus. In a typical city, there will be several SmartParks distributed throughout the city in distances of one to few miles. In order to represent this, six three-phase PEV parking lots (PL1 to PL6) are connected to bus 13 in Area 2 of the system. Bus 13 is an additional bus added to the original 12-bus system in order to connect the PEV SmartParks. Bus 13 is connected to bus 6 through a 22 kV/230 kV step-up transformer.

B. Modeling of the wind farm

The wind farm is equipped with a DFIG. It uses back-to-back PWM converters for variable speed wind power generation. The control objective of the grid side converter is to keep the dc link voltage constant regardless of the magnitude and direction of the rotor power. A stator oriented vector control approach is used where the direct axis current is used to control the dc link voltage and the quadrature axis current is used to control the reactive power and in turn the voltage at the point of common coupling. The control strategy is similar to [6]. The only difference is an additional PI controller is used to generate the reactive power command for the grid side converter from the voltage error signal. The objective of the rotor side converter is to control the active and reactive power from the stator. This is achieved by putting the d-axis of the rotor reference frame along the stator flux vector. The q-axis current reference is generated directly from the commanded electrical power and the d-axis current reference is generated from the stator reactive power command. The electrical power command is generated from the optimum operating point tracking strategy discussed in [6], when the wind speed is below a certain value. The pitch control does not work at that time and the wind turbine captures maximum possible energy at that wind speed. But, if the wind speed goes beyond a certain value, the pitch control limits the power generated by the wind turbine. The rotor side and grid side converter control strategy is shown in Fig. 2. The data for the 400 MW wind farm is taken from [7].

C. Modeling of the SmartParks

The SmartPark model in this paper is represented by a battery followed by a bidirectional three phase inverter (Fig. 3) [8]. The inverter generates a 2.08 kV three phase line-to-line rms voltage which is then passed through a 2.08kV/22kV step up transformer and connected to the SmartPark bus (bus-13 in Fig. 1). Between the inverter and the transformer there is a small (0.5mH) inductance. The control of the inverters is designed in such a way that each inverter can draw ±20 MW of active power. Considering each vehicle can draw ±25 kW, each SmartPark in this paper represents 800 vehicles aggregated together. Here '+' sign means the vehicles are selling power to the grid, i.e. they are in discharging mode and the '-' sign indicates that they are buying power from the grid, that means the vehicles are in charging mode. The control strategy for the PEV is presented in Fig. 4. In *d-q* reference frame, the active and reactive powers coming out of the inverter are [9]:

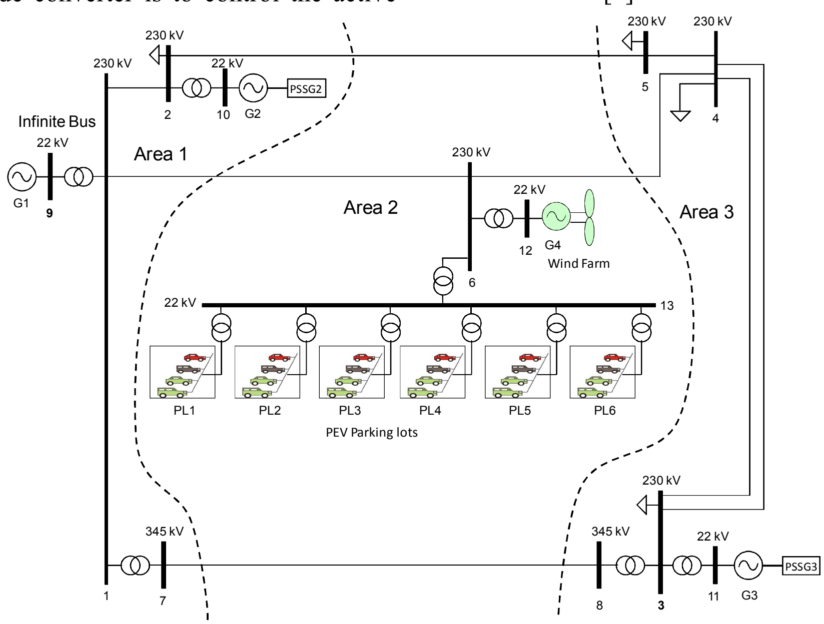

Fig. 1 Power system with a wind farm and six SmartParks

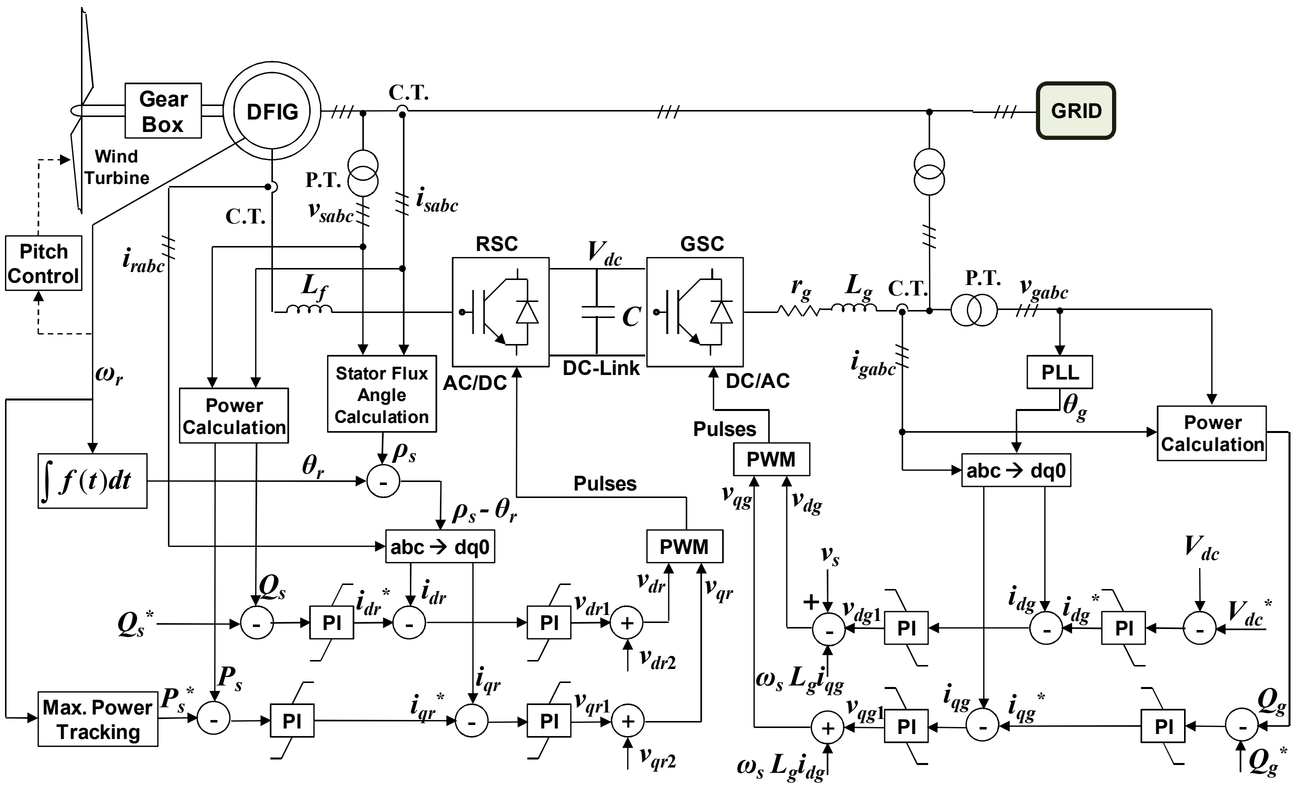

Fig. 2. Control of the wind farm

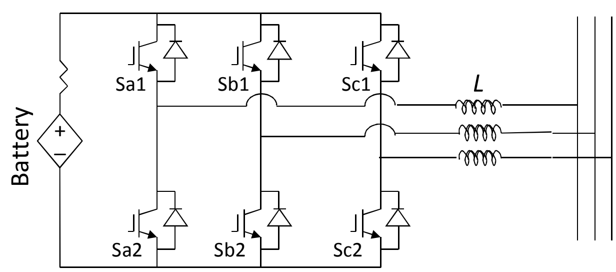

Fig. 3. The dc voltage source (battery) followed by the inverter

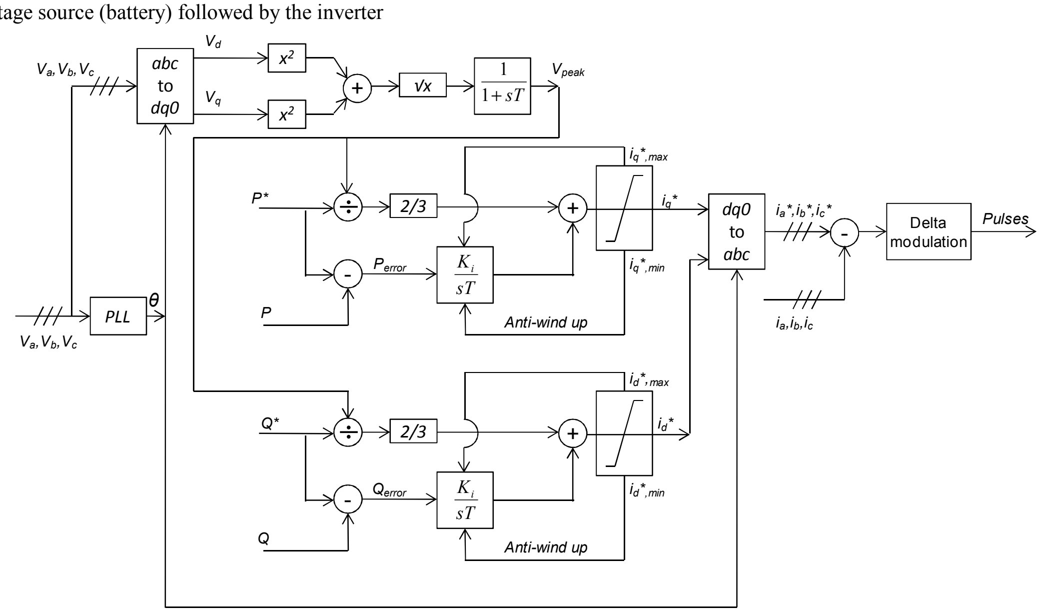

Fig. 4. The current control strategy for the SmartParks

$$P = (3/2)\cdot(v_{qs}i_{qs} + v_{ds}i_{ds}) \quad (1)$$

$$Q = (3/2)\cdot(v_{qs}i_{ds} + v_{ds}i_{qs}) \quad (2)$$

In synchronous reference frame the peak line-to-neutral voltage is in the *q*-axis and $v_{ds} = 0$. Therefore, the basis of the control is to command the currents in response to demanded power as

$$i_{qs}^{*} = (2/3\sqrt{2})\cdot(P^{*}/v_{peak}) + (K_i/s)\cdot(P^{*} - P) \quad (3)$$

$$i_{ds}^{*} = (2/3\sqrt{2})\cdot(Q^{*}/v_{peak}) + (K_i/s)\cdot(Q^{*} - Q) \quad (4)$$

The first component of (3-4) is based on the power equations (1-2) where v_{peak} is a filtered version of the line-to-neutral rms voltage. This portion creates quick response to sudden changes in commanded power. The integral term trims out the steady-state error. As shown in Fig. 3, a limit is placed on the commanded current and this is used to prevent integrator windup. The commanded *q*- and *d*-axis currents are then transformed to *a*-*b*-*c* variables where delta current-regulation is used to control the converter transistor switches.

The entire system is modeled on a real-time digital simulator (RTDS) platform. The simulation of the DFIG, the rotor side and grid side inverters and the vehicle inverters – all are carried out on the giga processor RTDS cards using small time step (1.5 µs) simulation.

III. FUZZY LOGIC BASED COORDINATED CONTROL

The basic idea behind this control is to use the SmartParks as energy storage devices. The energy storage devices can reduce the shock on the system when there is a drastic change in the wind speed. Moreover, with an energy storage device, the limit on wind power generation imposed by the pitch control during a wind gust can be increased and thus a more optimal utilization of the wind energy can be achieved. Now, the maximum possible amount of charging and discharging by the parking lots will depend on the state of charge of the batteries of the plug-in vehicles present at those parking lots at that particular moment. Therefore, a continuous monitoring of the aggregated amount of state of charge of the parking lots is necessary for this control strategy. Not only that, a continuous monitoring of the demand of wind power is also needed for the controller. This demand is compared with the actual wind power generated by the wind farm at that instant and the difference is used as one of the inputs to the fuzzy controller. Based on these two inputs, the controller outputs the charging and discharging commands for the SmartParks and the pitch angle reference for the wind farm. Fig. 5 shows the schematic diagram of the coordinated controller.

The variables, e.g. the demand and the available wind power, and the overall state of charge of the SmartParks – all of them vary dynamically in a random fashion in a practical power system and the range of variation is also quite large. Moreover, it is very difficult to find out a definite mathematical relation between these variables and the control action generated by the controller. Therefore, it is almost impossible to design a classical controller for this kind of coordinated control. The only thing an engineer can derive from practical knowledge is a set of rules which relate the variables with the control action. Due to this reason, fuzzy logic controller is the most suitable controller for this particular purpose. A typical fuzzy rule can be as follows:

If the difference between available wind power and the demand is *negative big* **and** the overall state of charge is *medium* **then** the SmartPark power command is *positive (discharging) big* and the pitch control reference is *very high*.

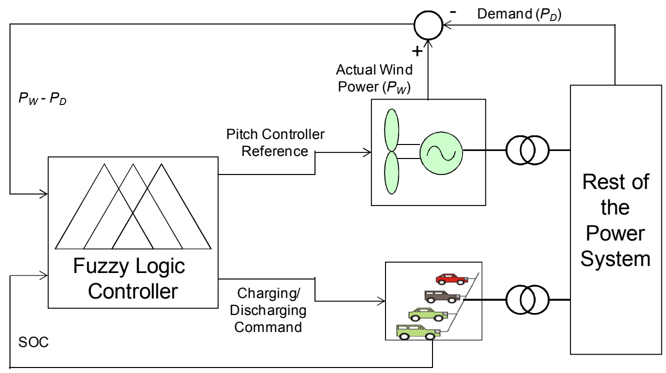

Fig. 5. Fuzzy logic based coordination controller

Here, *positive big*, *very high*, etc. are linguistic variables to qualify the input and output variables. All inputs to the fuzzy controller in this paper have triangular membership function with five linguistic states. The first input, i.e. the difference in available wind power and the demand is denoted by (P_W – P_D). Considering the average wind speed of that area varies from 9 m/s to 13 m/s, the variation of wind power generation is in between 180 MW and 430 MW. The demand is also assumed to vary in the same range. Therefore, (P_W – P_D) varies from -250 MW to +250 MW. The entire range is symmetrically distributed between five membership functions, such as: Negative Big (*NB*), Negative Small (*NS*), Zero (*Z*), Positive Small (*PS*) and Positive Big (*PB*). The other input, i.e. the total available state of charge of the SmartParks is denoted by *SOC*. In this paper, it is assumed that the charging and discharging of the SmartParks can occur only when the *SOC* is in the range of 20% to 80%. This entire range is symmetrically distributed between five membership functions as: Very Low (*VL*), Low (*L*), Medium (*M*), High (*H*) and Very High (*VH*). The input triangular membership functions are shown in Fig. 6.

It has been shown previously that Sugeno fuzzy model is effective for dynamic control actions [10]. Therefore, in this paper zero order Sugeno fuzzy model is used for calculating the outputs of the fuzzy controller. Each output has five firing strengths which are also symmetrically distributed along the entire range. The first output of the fuzzy controller, i.e. the pitch controller reference varies within a narrow range of

1.15 to 1.25. Without the fuzzy controller, the default value of this reference is set at 1.2. This output has five firing strengths denoted by Very Low (*VL*), Low (*L*), Medium (*M*), High (*H*) and Very High (*VH*). It is mentioned previously that each SmartPark can deliver or absorb +/-20 MW of power. Therefore, six of them as a whole can deliver or absorb +/-120 MW of power. Due to this reason, the second output of the fuzzy controller, i.e. the power command for the SmartParks also ranges in between +/-120 MW. This output also has five symmetrical firing strengths as Negative (charging) Big (*NB*), Negative Small (*NS*), Zero (*Z*), Positive (discharging) Small (*PS*) and Positive Big (*PB*). For each output, there are 25 rules. Therefore, the fuzzy controller as a whole has 50 rules. The rules for each output are shown in Tables I and II respectively. The rules generate the weights to each output firing strengths and the final output is calculated by center-of-area method.

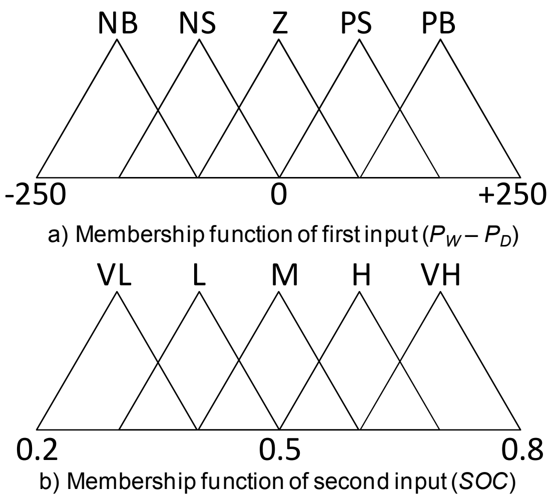

Fig. 6. Input membership functions

TABLE I
RULE BASE FOR PITCH CONTROLLER REFERENCE

SOC	$P_W - P_D$				
	NB	*NS*	*Z*	*PS*	*PB*
VL	VH	VH	VH	VH	VH
L	VH	VH	VH	VH	H
M	VH	VH	VH	H	M
H	VH	VH	H	M	L
VH	VH	H	M	L	VL

TABLE II
RULE BASE FOR POWER COMMAND OF THE SMARTPARKS

SOC	$P_W - P_D$				
	NB	*NS*	*Z*	*PS*	*PB*
VL	PB	PS	Z	NB	NB
L	PB	PS	Z	NB	NB
M	PB	PB	Z	NB	NB
H	PB	PB	Z	NS	NB
VH	PB	PB	Z	NS	NB

IV. RESULTS

The 12-bus power system, the wind farm and the SmartPark models, all are implemented on a RTDS and the fuzzy logic based coordination controller is implemented on an Innovative Integration M67 DSP card which is based on the Texas Instruments TMS3206701 processor. The M67 card operates at 160 MHz and is equipped with two A/D and two D/A conversion modules and is interfaced with the RTDS as shown in Fig. 7. The analog signals ($P_W - P_D$) and the *SOC* are sent by the RTDS to the M67. These are converted to digital signals through the A/D block of the DSP and are used to calculate the output of the fuzzy controller. These output signals are sent to RTDS as analog voltage signals in the range of ±10 Volts. These voltages are scaled proportionately inside the RTDS and used as the pitch controller reference for the wind farm and the charging discharging commands of the SmartParks at each sampling instant.

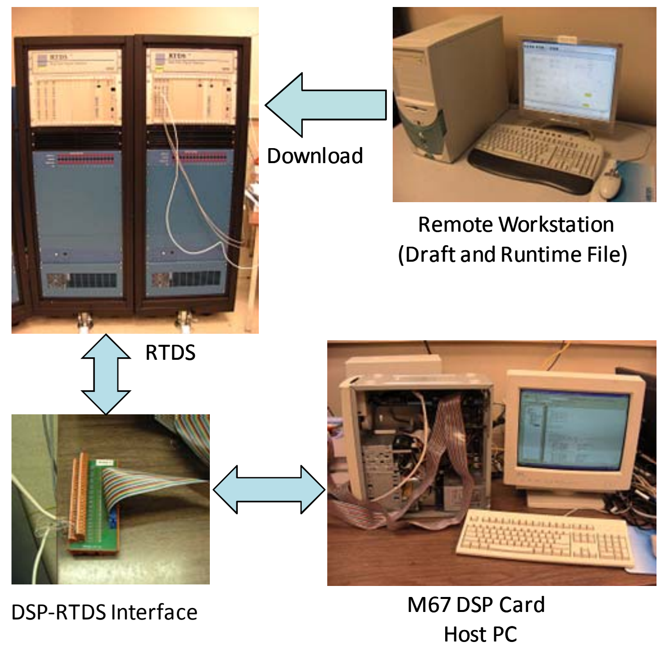

Fig. 7. Laboratory hardware set-up including RTDS and DSP

In order to demonstrate the effectiveness of the proposed coordination controller, following three case studies are presented.

A. Case Study 1

The first case study is presented in Fig. 8. Here, the demand of wind power is set at the value of 350 MW and the initial *SOC* is considered to be 50%. The initial wind speed is 11 m/s. The system is first run without the fuzzy controller. The power generated by the wind farm at this speed (with the pitch controller reference set at 1.2) is 345 MW which is almost equal to the demand. Now the wind speed is suddenly changed to 13 m/s. The wind power goes to 390 MW and this creates a sudden change in the power flow through line 1-6 and line 6-4 and the power flow oscillates for few seconds due to the large time constant of the pitch controller. The similar study is carried out with the fuzzy controller. Initially, when the wind speed is 11 m/s, the fuzzy controller is switched on. According to the rules shown in Table I, the pitch controller reference is changed to a higher value of 1.25 in order to capture more power from the wind farm. Now, the wind speed is changed to 13 m/s and it is observed from Fig. 8 that the steady state power obtained from the wind farm is almost 430 MW, which is much higher than that obtained without the controller. Also, as soon as the wind speed changes, the value of $(P_W - P_D)$ increases, which commands charging of the SmartParks following the rules given in Table II. Due to the use of the SmartParks in charging mode, it is observed that there is almost no change in the power flows through lines 1-6 and 6-4. Thus, the fuzzy coordination controller can perform as shock absorber. The entire oscillation in the power generation by the wind farm is absorbed by the SmartParks and the tie-lines do not experience any of those oscillations. During this charging period, the SOC of the SmartParks steadily increases which is shown in Fig. 9.

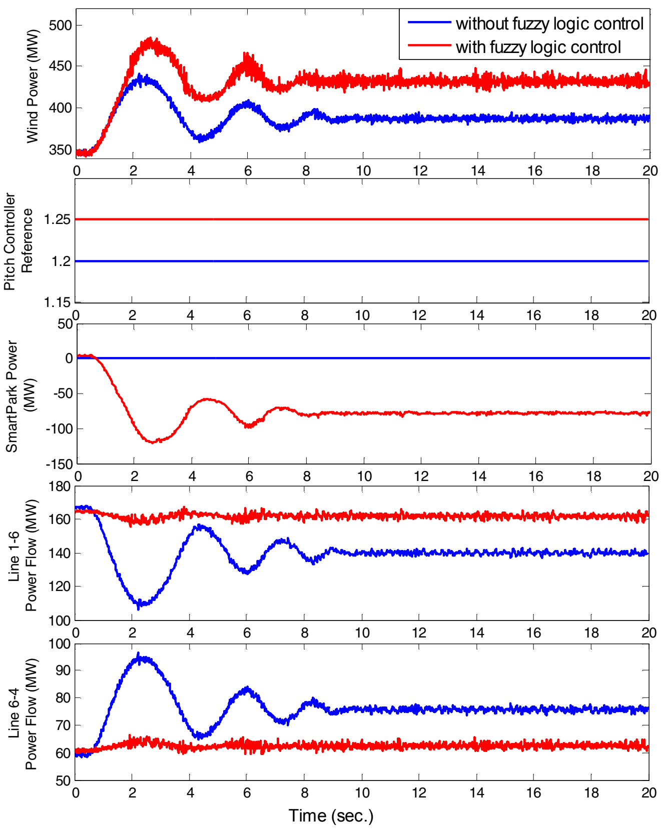

Fig. 8. Performance comparison with and without fuzzy logic controller for demand = 350 MW, SOC = 50% and wind speed changed from 11 m/s to 13 m/s

B. *Case Study 2*

Now the demand is changed to 400 MW in real time. The fuzzy controller changes the power commands of the SmartParks accordingly. The pitch controller reference is still maintained at high value of 1.25 according to Table I. After this, the wind speed is now decreased to 11 m/s. The generated wind power now comes back to 345 MW as before making $(P_W - P_D)$ negative. As soon as $(P_W - P_D)$ becomes negative, the fuzzy controller switches the power commands of the SmartParks from positive to negative changing the SmartParks from charging to discharging mode. As a result of this, there is again almost no impact on the tie-line power flows. Fig. 10 compares the performances with and without the fuzzy controller. It is observed that without the controller, when the wind speed falls, there is a significant change in the power flow through both the tie-lines. Also, it is observed that since the SmartParks changes from charging to discharging mode, the slope of the SOC changes as shown in Fig. 11.

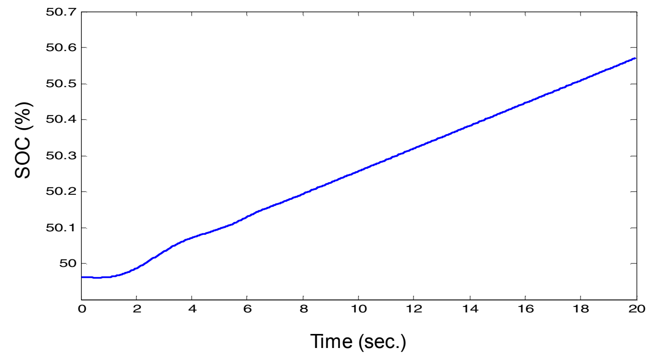

Fig. 9. The SOC during Case Study 1

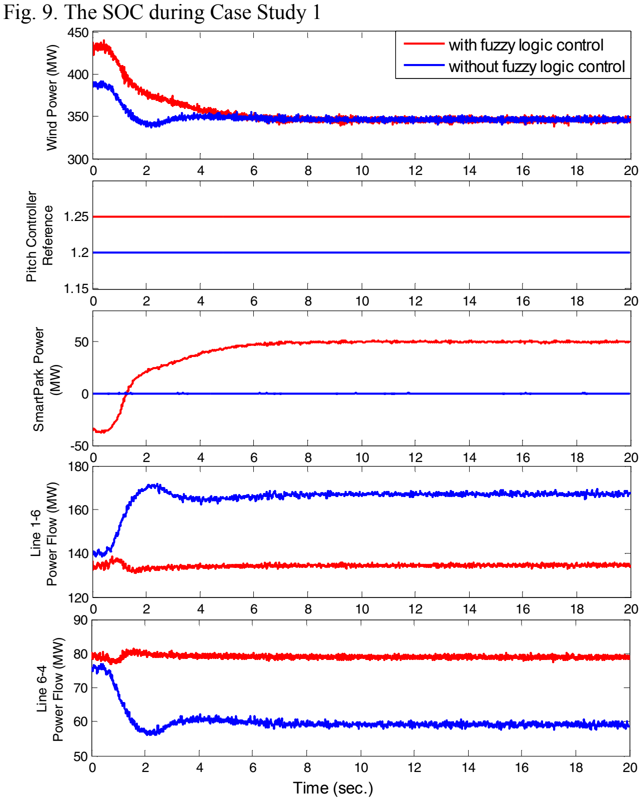

Fig. 10. Performance comparison with and without fuzzy logic controller when demand changed to 400 MW and wind speed dropped from 13 m/s to 11 m/s

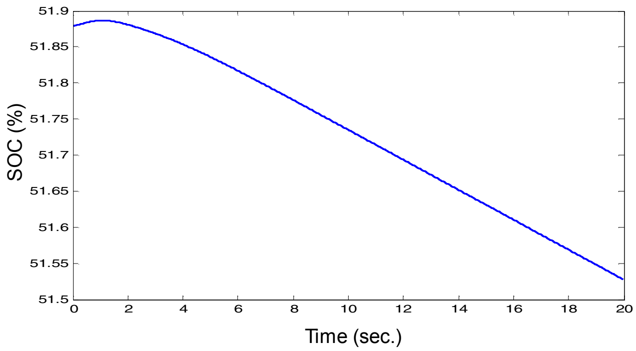

Fig. 11. The SOC during Case Study 2

C. Case Study 3

As a third case study, a very high value (70%) of initial *SOC* is considered. At this high value, the SmartParks cannot command high charging power because, as soon as the *SOC* will reach 80%, the SmartParks will stop functioning as shock absorbers. Here the demand is assumed to be very low (180 MW). The available wind power at 11 m/s (345 MW) is already very high compared to this demand. Now, the wind speed is further increased to 13 m/s making the difference ($P_W - P_D$) to be very high. The performance with and without the fuzzy controller is shown is Fig. 8. It is observed that without the fuzzy controller, the wind power increases to 390 MW and as a result, the power flow through the lines 1-6 and 6-4 oscillates with very high amplitudes. Now, with the same initial condition, if the fuzzy controller is switched on when the wind speed is 11 m/s, a certain portion of the excess power is used to charge SmartParks making the steady state values of the tie-line power flows to be different from the previous situation. Due to this reason, in Fig. 12, the tie line power flows does not start from the same initial condition. The pitch angle reference is also lower than the default value, since the demand is much lower than the available wind power. When the wind speed increases to 13 m/s in presence of the fuzzy controller, the pitch reference is dynamically adjusted to restrict the wind power generation as shown in Fig. 12. The available wind power finally settles to 365 MW. The dynamically changing charging commands of the SmatParks by the fuzzy controller keeps the oscillation amplitude of the tie-line power flows much lower than without the controller, though they oscillate around different steady state values as discussed before. In this case, the oscillation could not be damped totally as in Case Studies 1 and 2 due to the high value of initial *SOC* and the subsequent restricted use of the SmartParks and a lower value of pitch angle reference. The SOC for Case Study 3 is shown in Fig. 13. It is observed that it is fast approaching towards the 80% limit which justifies the restricted use of the SmartParks as shock absorber. The similar phenomenon could be observed when the initial *SOC* is very low and ($P_W - P_D$) is large negative. Other than these two extreme regions, the SmartParks can perform quite well as shock absorber and higher amount of energy can be captured from the wind farm with the application of fuzzy logic based coordinated controller.

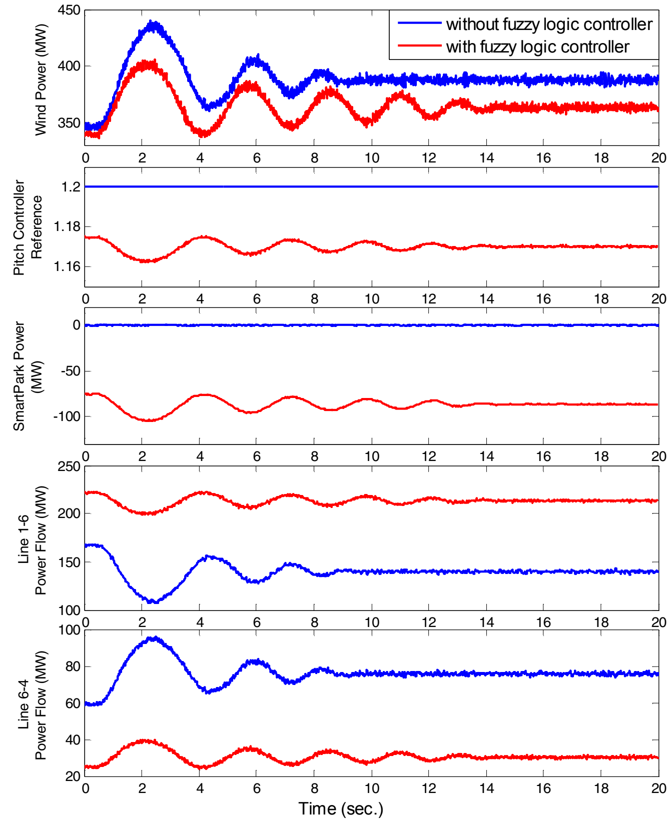

Fig. 12. Performance comparison with and without fuzzy logic controller for demand = 180 MW, SOC = 70% and wind speed changed from 11 m/s to 13 m/s

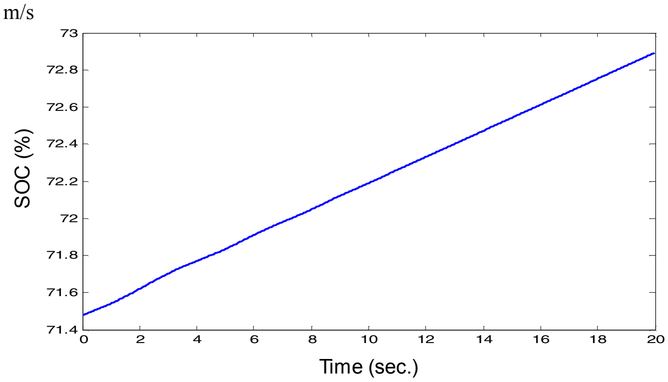

Fig. 13. The SOC during Case Study 3

V. Conclusion

A fuzzy logic based coordinated control of wind farm and SmartParks is presented in this paper. The proposed controller can reduce the shock on the tie-line power flows during drastic variation of wind speed and wind gusts and also improve the stability of the system. A real-time model of a 12-bus power system with a large wind farm and six SmartParks is developed. The details of the design of the fuzzy logic based coordinated controller has also been discussed. The performance of the fuzzy controller has been demonstrated with different case studies and its effectiveness as shock absorber is compared with a system having no such coordinated control. It is also observed that the fuzzy logic based coordinated controller can also help to maximize the utilization of wind energy available at a particular wind speed.

In order to optimize the performance of the SmartParks as shock absorbers especially during very high and very low state of charge conditions, the static rules of the fuzzy controller are not sufficient. In future, the effectiveness of the fuzzy controller with adaptive rules will be investigated.

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