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# A NOVEL DAMPING CONTROLLER FOR INTER-AREA OSCILLATION BY MEANS OF DFIG-BASED WIND FARM

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**Abstract-** It is widely accepted that inter-area oscillations maybe deteriorate the power system condition. These oscillations are due to the dynamics of inter-area power transfer in a large interconnected power network, which can severely limit the system performance. To provide a safe operation for power system stability, damping of these oscillations have become one of the main problems. This paper presents study of a DFIG to enhance the damping of an inter-area oscillation. In order to clarify the DFIG capability in mitigating inter-area oscillations, time domain simulations were carried out by MATLAB/Simulink. Simulation results reveal that the designed supplementary controller is efficient enough in damping power oscillations without any adverse interaction in other power system parameters.

**Keywords:** Reactive Power Modulation, Doubly Fed Induction Generators (DFIG), Inter-Area Oscillation Damping.

## I. INTRODUCTION

Recently, power systems are changing rapidly because of deregulation and fast growing demand. This situation obliges new considerations to maintain stability and reliability of the system. Transient stability analysis is considered when the power system is faced with large disturbances. Such disturbances can be cited as: sudden changes in load, generation or transmission system configuration due to fault or switching. Therefore, transient stability is an important criterion in power system design [1, 2].

Wind power energy has devolved greatly during past few years. Doubly Fed Induction Generators (DFIG) have gained much more attention in power generation recently due to their flexibility in decoupled control of active and reactive power [3]. The rotor slip characteristic of DFIG can be adjusted by voltage injected with controllable magnitude and phase from a back-to-back Voltage Source Converter (VSC) associated with rotor. This can provide reactive power support in order to maintain the terminal voltage beside of extracting maximum power generated by wind farm [4]. Other capabilities of DFIG is consists of lower converter costs and lower power losses and, flexible active and reactive power control capability through its rotor side converter (RSC).

To author's best knowledge, thanks to these salient considerable capabilities, in the recent year's researches have been motivated to utilize the DFIG for additional functions. One topic is transient stability enhancement and low frequency oscillation damping in power system with DFIG that has been discussed in [5-7].

Since the inter-area oscillation is a fact related to the rotor angle (active power) and voltage magnitude (reactive power), therefore active and reactive power modulation are effective methods for damping oscillations in power system. Reactive modulation is better for damping because it has not negative effects on electromechanical torque, but active modulation has negative effects on electromechanical torque. Many methods have been used in the design of auxiliary damping controllers in the literature [8, 9]. In [9] that uses a classic phase compensator for damping inter-area oscillations. In this paper an auxiliary PI damping controller based on reactive power modulation is granted to DFIG in order to mitigate the local and inter-area oscillations. The main objective of this controller is to adjust the reactive power which has no adverse effect on mechanical torque. This is the first time that the problem of inter-area oscillations is addressed by PI controller on a basis of reactive power modulation.

The paper is organized as follow as: In section II, a mathematical model is developed for the DFIG-based wind generator. Section III introduces DFIG-wind farm control including its active and reactive power control loops and electromechanical oscillations are described. Section IV also investigates the DFIG model for stability analysis including proposed controller aggregated with conventional controller. SectionV is dedicated to the simulation results and comparative tests between the PI and without controller scheme. Finally, in section VI the paper concludes with obtained results in section V.

## II. MODELING AND CONTROL OF DFIGs

The overall model of DFIG-based wind farms is consist of aerodynamics, turbine shaft dynamics, DFIG machine dynamics, rotor-side converter (RSC), DC-link capacitor dynamics and grid-side converter (GSC) control systems. The equivalent circuit of a DFIG can be described in different reference structures such as the stationary frame, the rotor frame, or the synchronous frame fixed to either the stator voltage [3].The grid-side and rotor-side converters are modeled as current source and voltage source, respectively. The DFIG model with the designed control technique was inserted in full dynamic simulation tool in order to evaluate the general effects in system dynamic behavior that result from this control scheme.

In order to analyze the operation of the scheme proposed to control the rotor-side converter, operational aspects concerning to the grid-side converter control will not be described since it is not the main goal of this paper. The grid-side converter is controlled to preserve the dc link voltage constant through control blocks based on instantaneous power theory [10] assuming it operates with unit power factor. In order to understand the impact of the presence of DFIG in the dynamic behavior of the power system (i.e., phenomena in the frequency range of 0.1 to 10 Hz), reduced order models have been used, ignoring the dc component and the fast transients of the stator currents and avoiding the inclusion of fast transients and the higher order harmonic components in the rotor injected voltages are neglected which are due to high switching frequencies of the electronic interfaces, as explained in [11, 12].

### A. DFIG Model

For modeling, it was assumed that the converters are ideal and the dc link voltage between the converters is constant. Figure 1 illustrates a schematic diagram of a DFIG-based wind-power unit, interfaced with the grid through the interface $T_{r1}$transformer. The DFIG stator circuit is directly linked to the low-voltage side of $T_{r1}$ However, the DFIG rotor circuit is interfaced with the same side through an ac-dc-ac, electronic, power converter. For the electronic converter, the transformer provides voltage matching. The q-axis was assumed to be $90^{o}$ ahead of the d-axis in the direction of rotation. Rotor and stator voltage equations in q-d reference frame can be acquired as follows:

$$v_s = r_s i_s + j\omega_s \lambda_s + \frac{d\lambda_s}{dt} \tag{1}$$

$$v_r = r_r i_r + j(\omega_s - \omega_r)\lambda_r + \frac{d\lambda_r}{dt} \tag{2}$$

where $v_s = v_{qs} - jv_{ds}$ and $v_r = v_{qr} - jv_{dr}$. The flux linkage expressions are given as follows:

$$\lambda_s = L_s I_s + M I_r \tag{3}$$

$$\lambda_r = L_r I_r + M I_s \tag{4}$$

where $L_s = L_{ls} + M$, $L_r = L_{lr} + M$, $\lambda_s = \lambda_{qs} - j\lambda_{ds}$, $\lambda_r = \lambda_{qr} - j\lambda_{dr}$, $I_s = i_{qs} - ji_{ds}$ and $I_r = i_{qr} - ji_{dr}$.

Transforming to a synchronously rotating d-q reference frame [11, 13, 14] the voltage Equations (1) and (2) become:

$$v_{sd} = R_s i_{sd} - \omega_s\, \lambda_{sq} + \frac{d\lambda_{sd}}{dt} \tag{5}$$

$$v_{sq} = R_s i_{sq} + \omega_s\, \lambda_{sd} + \frac{d\lambda_{sq}}{dt} \tag{6}$$

$$v_{rd} = R_r i_{rd} - (\omega_s - \omega_r)\lambda_{rq} + \frac{d\lambda_{rd}}{dt} \tag{7}$$

$$v_{rq} = R_r i_{rq} + (\omega_s - \omega_r)\lambda_{rd} + \frac{d\lambda_{rq}}{dt} \tag{8}$$

where $R_s$ and $R_r$ are, respectively the stator and rotor resistances $(\Omega)$, $\omega_s$ is the rotational angular speed of the synchronous d-q reference frame, $\omega_r$ is the rotational angular speed of the rotor, $v$ is the voltage (volts),i is the current (A), and $\lambda$ is the flux linkage (Wb) in the DFIG, $v_{qr}$ and $v_{dr}$ are not zero and are controllable via the rotor-side converter. Also the stator and rotor flux linkages are given by:

$$\lambda_{sd} = L_{ls} i_{sd} + L_m(i_{sd} + i_{rd}) = L_s i_{sd} + L_m i_{rd} \tag{9}$$

$$\lambda_{sq} = L_{ls} i_{sq} + L_m(i_{sq} + i_{rq}) = L_s i_{sq} + L_m i_{rq} \tag{10}$$

$$\lambda_{rd} = L_{lr} i_{rd} + L_m(i_{sd} + i_{rd}) = L_r i_{rd} + L_m i_{sd} \tag{11}$$

$$\lambda_{rq} = L_{lr} i_{rq} + L_m(i_{sq} + i_{rq}) = L_r i_{rq} + L_m i_{sq} \tag{12}$$

where $L_s$, $L_r$ are the stator and rotor inductances, $L_m$ is the mutual inductance. The electromagnetic torque manufactured by generator can be expressed as:

$$T_e - T_m = 2H\frac{d\omega_r}{dt} \tag{13}$$

where $T_m$ is the mechanical torque and $H$ is the inertia. $T_e$ is the electromagnetic torque and can be indicated as:

$$T_e = \frac{3}{2}\frac{n_p}{2}(\lambda_{mq} i_{rd} - \lambda_{md} i_{rq}) \tag{14}$$

$\lambda_{mq}$ and $\lambda_{md}$ are called the q-axis and d-axis air gap flux linkages, where $\lambda_{dm} = \lambda_{sd} - i_{sd}L_{ls}$, $\lambda_{mq} = \lambda_{sq} - i_{sq}L_{ls}$.

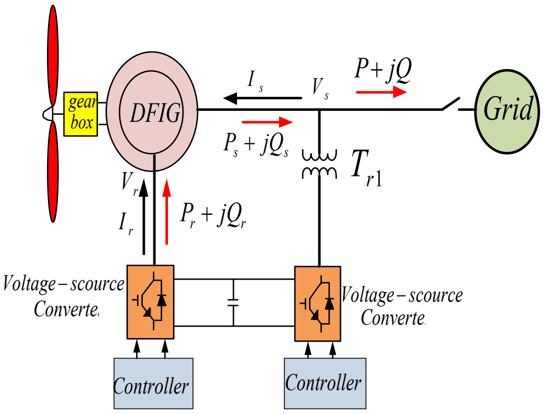


Figure 1. Grid-tied DFIG wind turbine system

## III. DFIG CONTROL

Controlling of the DFIG has two main goals. The first one is to accomplish maximum wind power capture, in this method control of active power and DFIG speed is the target. The second one is the control of the DFIG stator output reactive power [15]. The active and reactive power of the DFIG is mainly proportional to the rotor current, so with controlling the rotor current, we achieve appropriate active and reactive power. Rotor-side converter is able to control the rotor current.

### A. Control of Rotor-Side Converter (RSC)

The rotor- side converter control scheme consists of two cascaded control loops. The outer control loop manages the active and reactive power in machine. The active power can be controlled by $V_{qr}$, while the reactive power can be controlled by $V_{dr}$. The inner current control loop manages separately the d-axis and q-axis rotor current components, $i_{rd}$ and $i_{rq}$, according to a synchronously rotating reference frame which is not included in our investigation [11].

### B. Control of GRID-Side Converter (GSC)

The main purpose of the grid-side converter is to fix the DC bus voltage, maintain the input current sinusoidal and to control the input power factor. If there is a balance in active power between AC and DC side, DC bus voltage can be stable. Therefore with active power control of the AC-side, DC bus voltage can be maintained fixed. As the AC-side voltage is constant, the input active power in the DC-side can be controlled to fix the DC bus voltage. The input power factor control is actually identical with the control of the input current reactive power component. So the grid converter control system is divided into two sections: one is speed control and the other is the current control [16].

### C. Electromechanical Oscillation

In this part, electromechanical oscillations are described. Also a nonlinear control scheme with DFIG-based wind farm (active and reactive power modulation) to damp inter-area oscillations is proposed. Electromechanical oscillations are due to the dynamic of inter-area power transfer in a large inter connected power network that can seriously limits the operation of system and in some condition induces stress in the mechanical shaft of synchronous generators. Usually the electromechanical oscillations divide in two types [17], [18]:

1) Local mode, the local mode oscillations are due to swing of one synchronous generator against another generator in same area, they usually have frequencies from 1 to 3 Hz.

2) The inter-area mode: the inter-area oscillation involves oscillations of a group of generators in one area against a group of generators in another area. They are in range of less than 1Hz.

Typically it is more difficult to control inter-area oscillation than local oscillation in actual power systems [17], [19]. Active and reactive power modulation for inter-area oscillations damping are effective methods. Furthermore the active power modulation is better for damping oscillations. However, wind farm with active power modulation deteriorates the wind turbine's shaft performance (Damping of the shaft mode decreases) because the torsional oscillation frequency in wind turbine is pretty low. Furthermore, reactive power modulation has not negative effects on the wind turbine's shaft and electromechanical torque, because reactive power is not straightly associated with the wind turbine's shaft and electromagnetic torque. Therefore in this paper in order to achieve better performance, the auxiliary control loop supplemented for modulate reactive power in rotor side converter of DFIG's.

## IV. DFIG MODEL FOR STABILITY STUDIES

In order to obtain decoupled control of active and reactive power of the DFIG, vector control scheme based on proportional integral (PI) controllers was suggested and has been widely used in the industry due to their simple structure and robust performance, easy to design and low cost [9]. The decoupled control of DFIG has several different PI controllers. To achieve for better damping of inter-area oscillation in DFIG based-wind farm, many methods have been used in design of auxiliary damping controllers. As instance, in [9] a classic phase compensator is implemented. The DFIG control in [19] is based on flux magnitude and angle control (FMAC). An auxiliary damping control is added to improve the flux angle reference, which is acquired from a proportional-integral (PI) controller to follow the active power reference.

In [19], an auxiliary signal extracted from the rotor speed is added to the rotor phase angle control to improve the low frequency damping of inter-area oscillations. Figure 2 demonstrates detailed rotor side converter control aggregated with PI controller involved in the reactive power modulation in a DFIG RSC. The reactive power modulation will modulate the reactive power reference value, while the active power modulation will not considered in this paper due to negative effects which earlier is cited above. PI controllers are employed in the control loops such that the measured power (reactive power) tracks the modulated reference power values.

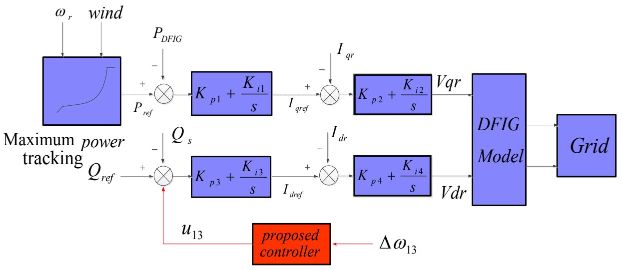


Figure 2. The rotor side converter controller aggregated with proposed controller

The precise configuration of proposed controller is demonstrated in Figure 3. It consists of a washout filter, two lead-lag compensators, a gain block, and limiter in order to constrain the output of controller. The output is added to reactive power control loop of the DFIG RCS. The damping controller is designed so as to provide an extra electrical torque in phase with speed deviation in order to enhance the damping of oscillations.

Traditional methods of design, based on some characteristics of the output curves for particular inputs applied on the system, were used to acquire initial values for the gains of the controllers. Then, the gains were exactingly regulated for trying and error through various simulations, in order to obtain least difference for the controlled variables include in design. After this long operation of adjusting, the values acquired for the PI controller gain are shown in Appendix.

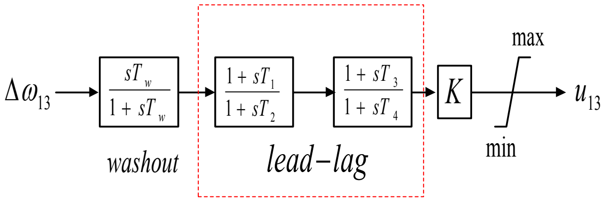


Figure 3. Detailed proposed damping controller

## V. SIMULATION RESULTS

### A. Case Study

The test system shown in Figure 4 is considered in this research. The system represents two areas connected to a large system, where voltage regulators are included and modeled with an IEEE type 1 model [17]. The DFIG is represented by the model described in section II. Loads are modeled as constant impedance. The considered control strategy is tested in the power system shown in Figure 4, where a three-phase fault is applied between line7 and 8 at time 35sec and lasts for 0.1sec. The symmetrical network topology considered (without the wind farm) is usually employed in the literature for showing local and inter-area oscillations [17, 22] and for understanding the subject in order to solve more complex networks. The data of the network, except the DFIG-based wind farm power production of about 200 MW in order to improve the voltage profile in each area, are given in [17].

The system shows both local and inter-area oscillations when a disturbance occurs in the system. A power flow analysis indicates that in Area 1, G1 and G2 are delivering 662.5 and 700 MW, respectively, whereas in Area 2, G3 delivers 719 MW and G4 delivers 700MW. Then, Area 1 is exporting 414 MW to Area 2. A wind farm based on DFIG is connected to the grid in (bus 7) and represented by one aggregated DFIG. The rated exporting level of the wind farm is 200 MW. It is important to note the difference between the powers of each area when they are compared with the delivered power of the wind farm (200 MW). In order to show the inter-area mode, the angular speed of G1 is compared with the angular speed of G3. On the other hand, the local mode is shown through the difference between the angular speeds of generators 2 and 1.

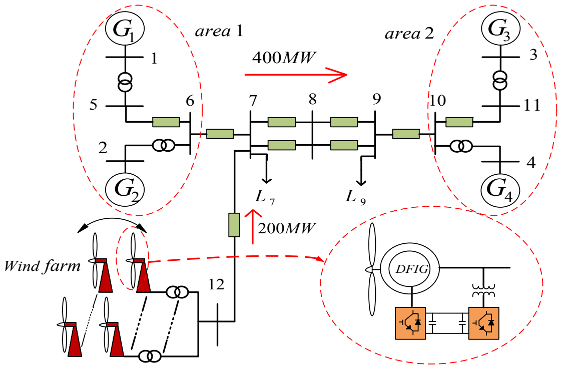


Figure 4. Schematic diagram of two-area system with a DFIG-based wind turbine farm system

The parameters of the synchronous generators are shown in [21] along with turbine governor control blocks and parameters. The parameters of DFIG and wind turbine shaft, and RSC and GSC controls are shown in [8, 15]. The system has several oscillation modes: 1) local electromechanical oscillations (1.2 Hz) due to one synchronous machine swinging against a local area, 2) the inter-area mode (0.75 Hz) due to Area 1 swinging against Area 2, and 3) the wind turbine shaft mode (0.87 Hz) [8]. Wind speed is assumed to remain constant in this study.

### B. Simulation Results and Discussion

To further demonstrate the effectiveness of the proposed controller, a comparison between (with and without) PI controller is performed, that exhibits the superior performance of system with PI controller. Firstly, the local mode oscillations between generator G1 and G2 are clarified in Figure 5. As shown in Figure 5, it is obvious that the system is unstable resulting in inter-area oscillation, but with proposed supplementary controller, the damping of the local mode is quite satisfactory when compared to the initial response of the power system.

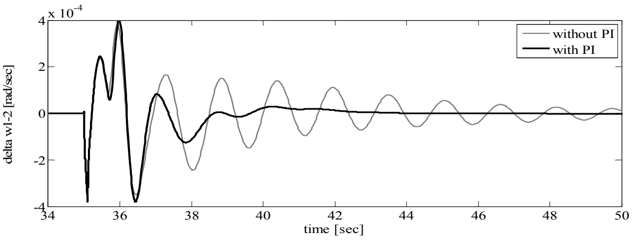


Figure 5. Local mode oscillations ($\omega_2 - \omega_1$) with and without PI controller

The inter-area mode oscillations, which are the adverse oscillations between generators from one area to another area is clarified in this part. Figure 6 reveals the swings of generator speeds between generator 1 and generator 3. Without proposed controller, the speed deviation is faced with large oscillations and it is about to increase as the time is going on. Furthermore, when auxiliary controller is applied, the oscillations were greatly reduced and the speed deviations become zero after few seconds.

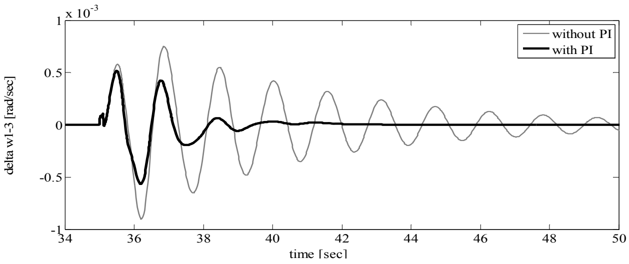


Figure 6. Inter-area mode oscillations ($\omega_3 - \omega_1$) curves

The power transfer from area 1 to area 2 in normal condition without any wind farm is about 400 MW. In addition, when the wind farm is linked to power system and generates about 200 MW, the power transferred from area1 to area2 modifies and reaches to about 500 MW. Figure 7 illustrates the power transfer between two areas with and without PI controllers. It is observed from this figure that, the power transfer recovers itself after few second when auxiliary controller operates.

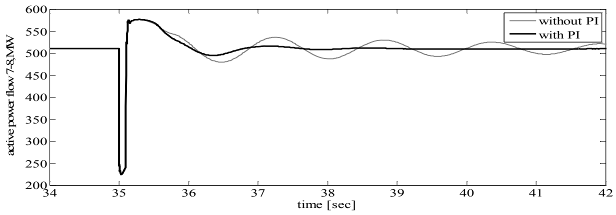
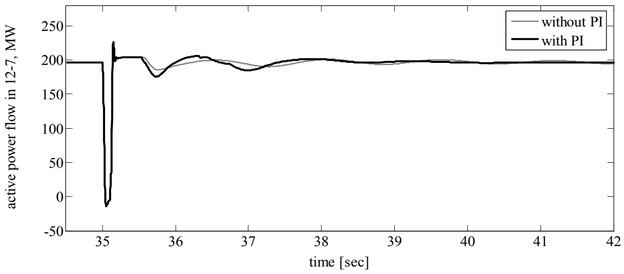
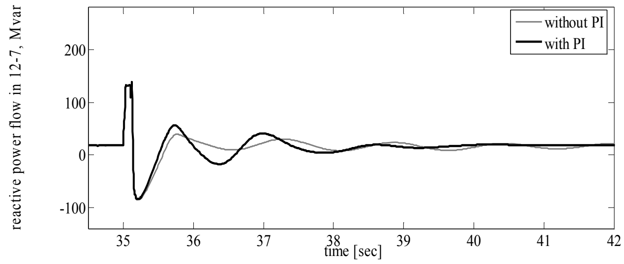


Figure 7. The power transferred from area1 to area 2

Figure 8 demonstrates the active and reactive power flows from DFIG to grid. It should be noted that, however active power is faced with oscillations, but after few seconds the power oscillations alleviate and fixed active power transmits to the grid.



(a)



(b)

Figure 8. (a) Active power transferred from DFIG to Grid
(b) Reactive power transferred from DFIG to grid

The current which flows from area1 to area2 is included in Figure 9; furthermore, the voltage of bus 10 is covered in Figure10.

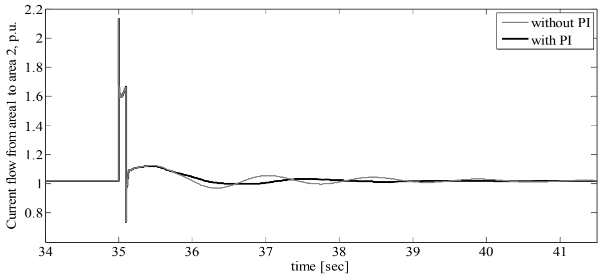


Figure 9. Current flow from area1 to area 2

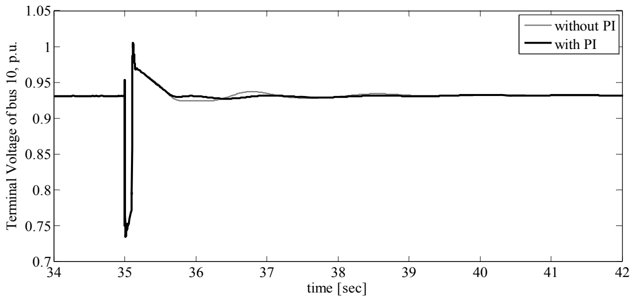


Figure 10. Terminal voltage of bus10 [p.u]

## VI. CONCLUSIONS

In this paper, a novel PI controller design is investigated for DFIG-wind power penetration in inter connected system oscillation damping. The PI control loop for DFIG modulates reactive power in rotor side converter to damp the inter-area oscillations. It is great of interest that, in this paper, not only inter-area oscillations are alleviated significantly, but also the proposed controller is capable of mitigating local mode oscillation. It is observed that the system performance under test without any damping controller would be considerable poor and as time passed, the oscillation increase and the system can be unstable. To provide a safe operation for power system stability, damping of these oscillations have become one of the main problems. Time domain simulations were carried out in order to verify the superior performance of proposed controller. In order to validate the claims the well-known two-area four-machine power system aggregated with DFIG is simulated using MATLAB/Simulink.

## APPENDIX

**Gains for PI controller:**

$k$=90, $T_w$=1.22, $T_1$=0.42, $T_2$=2.03

## NOMENCLATURES

$n_p$: Number of pole pairs
$J$: Inertia constant
$\omega_m$: Rotational angular speed
$D_m$: Damping of the shaft system
$T_m$: Mechanical torque
$T_e$: Electromagnetic torque
$\omega_s$, $\omega_r$: Stator and rotor rotating speed
$\omega_{slip}$: Slip rotating speed
$v_{sabc}$: Stator voltage
$v_r$ : Rotor voltage
$i_{sabc}$: Stator current
$i_r$ : Rotor current
$R_s$, $R_r$: Stator and rotor resistances
$\lambda_{sabc}$: Stator flux linkage
$\lambda_{rabc}$: Rotor flux linkage
$v_{sd}$, $v_{sq}$: Stator voltages in d and q axis
$i_{sd}$, $i_{sq}$: Stator currents in d and q axis
$\lambda_{sd}$, $\lambda_{sq}$: d and q axis stator flux linkages
$v_{rd}$, $v_{rq}$: Rotor voltages in d and q axis
$i_{rd}$, $i_{rq}$: Rotor currents in d and q axis
$\lambda_{rd}$, $\lambda_{rq}$: d and q axis rotor flux linkages

$L_s$, $L_r$: Stator and rotor inductances
$L_m$: Mutual inductance
$L_{ls}$, $L_{lr}$: Lakege inductances of stator and rotor
$Q_r$: Rotor reactive power
$\Delta\delta$: Rotor angle difference
$\Delta\omega$: Difference between speeds
$P_{Grid}$ : Active power of grid
$P_{ref}$ : Refrence value for active power
$Q_{Grid}$ : Reactive power of grid
$Q_{ref}$ : Refrence value for reactive power

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