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COMPARISON OF PID AND FUZZY CONTROLLED DUAL INVERTER-BASED SUPER CAPACITOR FOR WIND ENERGY CONVERSION SYSTEMS

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Abstract - *The intermittency of wind energy requires energy storage devices for matching the dynamic variation of wind power in electric power grid. The energy storage systems like supercapacitors and batteries when interfaced with converters in wind power system further increases cost and power losses. Therefore, a direct integration method for supercapacitors is used to overcome the short-time power fluctuations in wind power systems. In this method a dual inverter topology is used for grid connection and interfacing supercapacitors and to reduce the fluctuations in the output, corresponding to dynamically fluctuating input, the switching controller is implemented using PID and FUZZY compensator. The direct integration scheme using PID and FUZZY controller are simulated using MATLAB/SIMULINK and the simulation results are compared by verifying the effectiveness of the system in suppressing short-time power fluctuations in wind.*

Key Words: *Dual inverter, direct integration Scheme for Supercapacitor, fuzzy controller, and wind energy*

1. Introduction

An ever-increasing demand for electric energy and with the depletion of fossil fuels, renewable sources of energy are emerging as an alternative. Among them, wind energy has become one of the main-stream of energy source. Wind is naturally abundant resource and it is one of the cleanest ways to produce electricity and the fastest growing renewable resources.

Though wind is considered as an imminent energy source, wind power fluctuation due to continuous variation of wind speed is further a serious issue. In order to overcome these short-term power fluctuations a suitable energy storage system like supercapacitors is actively pursued in wind power system. Supercapacitors can be connected wind power systems in two ways. In first category, direct connecting in-between dc-link of back-to-back converter system as shown in Fig. 1(a). However it is the simplest connection, we would not get maximum utilization of the supercapacitor bank owing to dc-link voltage limitation set by the grid-side inverter. This consequence can somewhat be reduced if an intermediate dc-dc converter is placed between the supercapacitor and the dc-link as shown in the Fig. 1(b). This dc-dc converter needs to possess bidirectional power flow capability for which two fast switching devices rated to peak power are required. This would increase the system cost and power loss [1] [2]. In the second category, the common ac-bus system is used for power exchange, as shown in Fig. 1(c), and it requires an additional dc-dc converter, dc-ac inverter and a coupling transformer. Coupling transformer is a special case of inductive coupling of two circuits by means of mutual inductance provided by a transformer. It ensures maximum power transfer even though output impedance is not equal to load impedance. But with the use of addition converter and coupling transformer increases the overall system cost, power- loss and complexity, which would be absent if direct integration scheme with full controllability is available.

This paper discuss about a direct integration scheme for supercapacitors with the use of gird-side inverter [3], as shown in Fig. 1(d). The dual inverter system show in the Fig. 1(d) is formed by cascading two inverters through a coupling transformer. The two inverters are named as main inverter and auxiliary inverter. The main inverter is powered by the wind turbine which is coupled to the permanent magnet synchronous generator's rectified output and the auxiliary is directly connected to the supercapacitor.

The high-power low speed main inverter operates at fundamental frequency and produces a square wave output. The low power high speed auxiliary inverter eliminates the harmonics produced by the square wave output. The main inverter is constructed using devices like gate turn-off thyristors (GTOs), integrated gate-commutated thyristors (IGCTs), or emitter turn-off thyristors (ETOs) as it is high powered. On the other hand, the auxiliary inverter is constructed using devices like insulated gate bipolar transistors (IGBTs). This particular way of splitting power and frequency arrangement helps to reduce power loss [4].

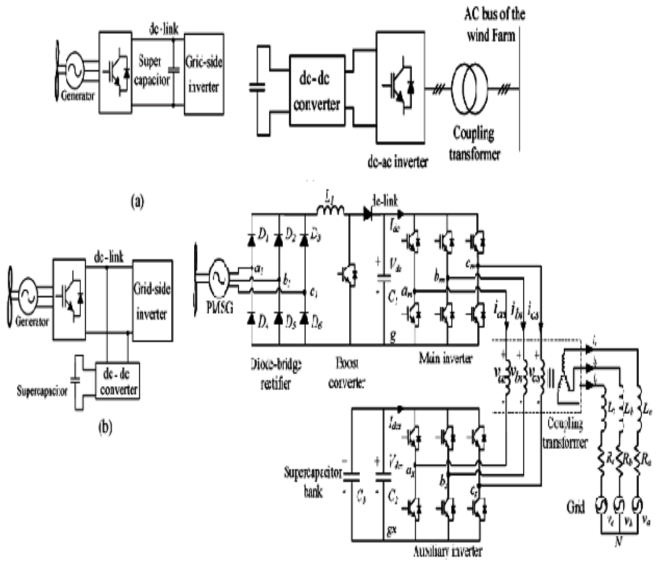


Fig. 1: Interfacing methods for supercapacitor energy storage system (a) direct connection to dc-link (b) connection to dc-link through DC-DC converter (c) connection to common ac bus system (d) Proposed grid side-inverter with direct connection

2. Dual Inverter based Direct Integration Scheme

The proposed system shown in Fig. 2 consist of Wind Turbine, Permanent-magnet Synchronous machine, three phase diode rectifier, Boost Converter , DC/AC main inverter, DC/AC auxiliary inverter or dual inverter and Supercapacitor. The PMSG is coupled to wind turbine and its output is fed to the diode rectifier. The rectified output of wind generator acts as input to boost convertor to control the dc-link voltage. The main inverter of dual inverter is connected across dc-link while the auxiliary inverter is directly connected to supercapacitor. The two inverters are cascaded and connected to the grid through a coupling transformer.

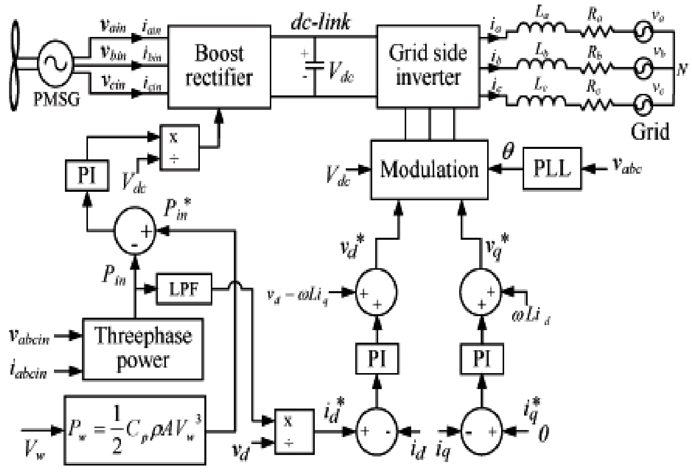


Fig. 2: Controller Block Diagram of the proposed system

2.1 Modelling of wind turbine

A wind turbine is that converts wind kinetic energy into electric power. The kinetic energy of the wind gets transformed into mechanical torque. The wind turbine generated Torque is transferred through generator shaft to rotor of the generator.

Wind turbine power is given by

$$P = \frac{1}{2} \rho A V^3 Cp(\lambda, \beta) \quad (1)$$

Where ρ is the air density (kg/m^3), A is the Swept Area (m^2), C_p = Coefficient of Power, V is the wind velocity (m/s), λ is the tip speed ratio, β is the pitch angle.

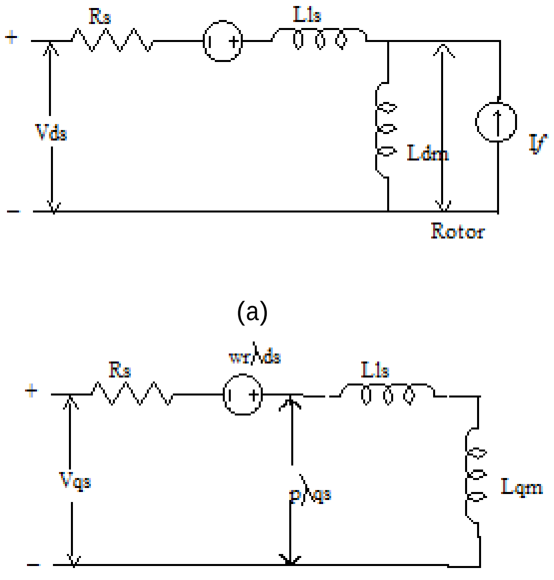
2.2 Modelling of PMSG

A general d-axis and q-axis model of synchronous generator is shown in fig 3.It is assumed that the rotor flux concentrated along d-axis and zero flux along q-axis.

The stator flux-linkages equations are

$$V_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \quad (2)$$

$$V_{qs} = -R_s i_{qs} - \omega_r \lambda_{ds} + p\lambda_{qs} \quad (3)$$



(a)

(b)

Fig. 3: (a) d-axis circuit, (b) q-axis circuit

Where λ_{ds} and λ_{qs} are the stator flux-linkages along d-axis and q-axis.

$$\lambda_{ds} = -L_d i_{ds} + \lambda_r \quad (4)$$

$$\lambda_{qs} = -L_q i_{qs} \qquad (5)$$

λ_r is the rotor flux, and L_d and L_q are the stator d-axis q-axis self-inductances, where

$$\lambda_r = L_{dm} I_f \qquad (6)$$

$$L_d = L_{ls} + L_{dm} \qquad (7)$$

$$L_q = L_{ls} + L_{qm} \qquad (8)$$

In a PMSG for constant, $\frac{d\lambda_r}{dt} = 0$. Therefore equ (2), equ(3) is given by

$$V_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \qquad (9)$$

$$V_{qs} = -R_s i_{qs} + \omega_r i_{ds} - \omega\lambda_r - L_q p i_{qs} \qquad (10)$$

The electromagnetic torque by the synchronous generator is detemined by the equation

$$T_e = \frac{3p}{2}(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \qquad (11)$$

Substituting equ (7) and equ (8),we have

$$T_e = \frac{3p}{2}[\lambda_r i_{qs} - (L_d - L_q) i_{ds} i_{qs}] \qquad (12)$$

The rotor speed ω_r is given by

$$\omega_r = \frac{p}{js}(T_e - T_m) \qquad (13)$$

Based on the above equations computer simulation of the permanent magnet synchronous machine is determined

2.3 Three phase diode rectifier

A rectifier is a circuit that converts ac input voltage to dc output voltage. The process of conversion of ac input to dc output is called rectification. Semiconductor diodes are used widely in power electronic circuits for the conversion of power from ac to dc. A rectifier employing diodes is known as uncontrolled rectifier.

2.4 Boost converter

The DC-DC boost converter is used to convert uncontrolled dc voltage to controlled dc output voltage.

The per-phase equivalent of the dual inverter system is shown in Fig. 4, where the output voltage vector ($\bar{V}_r$) is equal to addition of main inverter voltage vector ($\bar{V}_M$) and auxiliary inverter voltage vector ($\bar{V}_A$) as in equation (14).

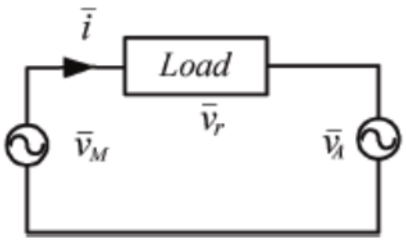


Fig. 4: Per-phase equivalent circuit of dual inverter

The real power delivered to the load can be expressed as the dot product of output voltage vector ($\bar{V}_r$) and load current ($\bar{\imath}$) as in equation (15).

$$\bar{V}_r = \bar{V}_M + \bar{V}_A \qquad (14)$$

$$P_L = \frac{3}{2}\bar{V}_r . \bar{\imath} \qquad (15)$$

$$P_L = \frac{3}{2}(\bar{V}_M + \bar{V}_A).\bar{\imath} = P_M + P_A \qquad (16)$$

$$P_A = \frac{3}{2}(\bar{V}_r - \bar{V}_M).\bar{\imath} \qquad (17)$$

According to equation 17, when the output power is constant, the battery power P_A has linear relationship with main inverter dc-link voltageV_{dc}. So the supercapacitor power can be controlled by controlling the main inverter dc-link voltage thus the maximum power point of wind turbine can indirectly be tracked.

The maximum power point tracking controller block diagram is shown in Fig. 5.

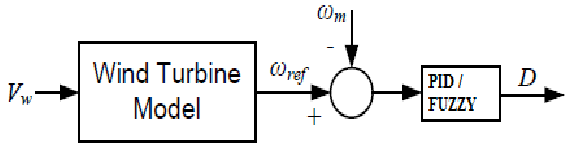


Fig. 5: Controller Block Diagram

In the above Fig 4, the obtained generator power is compared with the reference output power, and the error is fed to PID/FUZZY controller which generate a voltage reference for boost rectifier. This voltage reference is normalized to produce the modulation index for boost rectifier [5] [6].

Fuzzy Logic Controller

The control algorithm of a process that is based on fuzzy interface system is defined as a fuzzy logic control. The fuzzy controller principle is to increase or decrease the generator speed for corresponding increase or decrease in the estimated output power.

The input variables are change in output power and change in generator speed which are converted into corresponding fuzzy sets with human descriptive terms

BIG, MEDIUM, SMALL, ZERO. This action is performed by the "fuzzification block". The variables are then described by the membership function. Rules Table 1 gives descriptive rules like "if the change in power output is positive and change in speed is positive and maximum power is positive then BIG". Finally, the fuzzy set of output value reference change in speed is "deffuzzified" to get the actual value [7].

In the below Table 1 P mean positive, ZE means zero and N means negative

PVB –power value big. PMED- power value medium PSMA- power value small.

Similarly the other rules are designed.

Table 1: Rules tables for the fuzzy controller

Δ wr ΔP	P	ZE	N
PVB	PVB	PVB	NVB
PBIG PMED	PBIG PMED	PVB PBIG	NBIG NMED
PSMA ZE	PSMA ZE	PMED ZE	NSMA ZE
NSMA NMED	NSMA NMED	NMED NBIG	PSMA PMED
NBIG NVB	NBIG NVB	NVB NVB	PBIG PVB

2.5 Modulation and control of grid-side Inverter

The main inverter operates in six-step mode generating square wave output. The auxiliary inverter is used to suppress the harmonics produced by the square wave output. As the auxiliary inverter operates at high switching frequency utilizes space vector modulation method. Therefore, the overall modulation is a combination of the six-step mode and SVM [8].

The grid-side inverter controller employs an inner current controller and an outer power controller as shown in fig 2. The grid voltage and current injected into the grid are converted into the synchronous reference frame. The direct component i_d of the inverter current controls the active power exchange with the grid while the quadrature component i_q controls the reactive power. These active and reactive current references are then compared with the actual current components and the errors are passed through PID and Fuzzy controller to produce voltage references.

The amplitude of voltage reference is given by

$$A_m = \sqrt{V_d^* + V_q^*} \tag{18}$$

The initial phase angle of the reference is given by

$$\alpha_m = \tan^{-1} \frac{V_q^*}{V_d^*} \tag{19}$$

3 Supercapacitor Size

The main of power fluctuations is due to continuous change in wind speed. Then the size of supercapacitor is also a function of change in wind speed. The wind power can be expressed as the sum of a DC quantity and a series if harmonics [9] as shown below

$$v_\omega = V_{\omega o} + \sum \Delta V_{wi} \sin(\omega_i t) \tag{20}$$

$$v_w(t) = V_{\omega o}(1 + 0.2 \sin(\frac{2\pi}{T} t)) \tag{21}$$

$$P = \frac{1}{2} \rho ACpV(t)^3 \tag{22}$$

Where v_ω is the instantaneous wind speed, $V_{\omega o}$ is the mean wind speed, ΔV_{wi} is the harmonic amplitude, ω_i is the angular frequency ($f = {}^1/_T = {}^\omega/_{2\pi} = 0.1 \sim 10Hz$, ρ is the density of air, swept area of the wind turbine is A, and Cp is the power coefficient.

The required capacity of the supercapacitor bank is given by

$$E_{sc,discharge} = \int_{t1}^{t2} (P(t) - P_{grid}(t))\, dt \tag{23}$$

$$C_{sc} \geq \frac{2E_{sc,discharge}}{(V_{sc,H}^2 - V_{sc,L}^2)} \tag{24}$$

Where $E_{sc,discharge}$ is the energy given by the supercapacitor during the discharge period, $t_1 \text{ and } t_2$ are the starting and ending time of discharge period. $V_{sc,L} \text{ and } V_{sc,H}$ are the limits of supercapacitor voltage.

4 Simulation Results

The direct integration scheme for supercapacitor using PID and FUZZY controlled is simulated using MATLAB/SIMULINK. The wind profile is shown in Fig. 6 with an average speed of 10 m/s, and the generated output current and voltage are shown in Fig. 7 and Fig. 8. Fig. 9 shows the dc-link currents of main inverter and auxiliary inverter. The simulation results are compared to verify the efficacy in mitigating short–time power fluctuations in wind energy system.

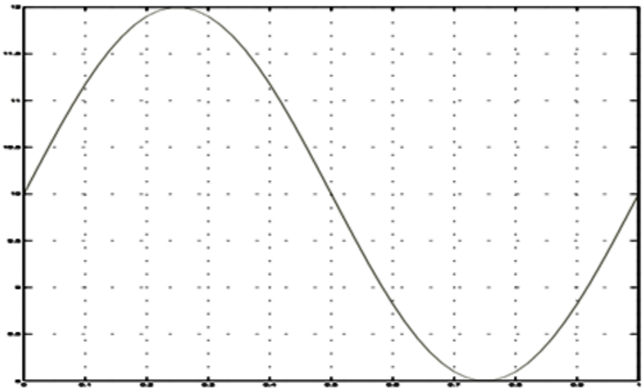


Fig. 6 Wind Profile

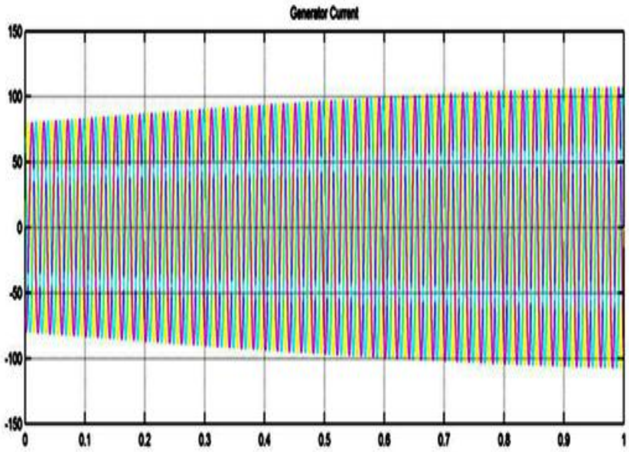


Fig.7:Generator current

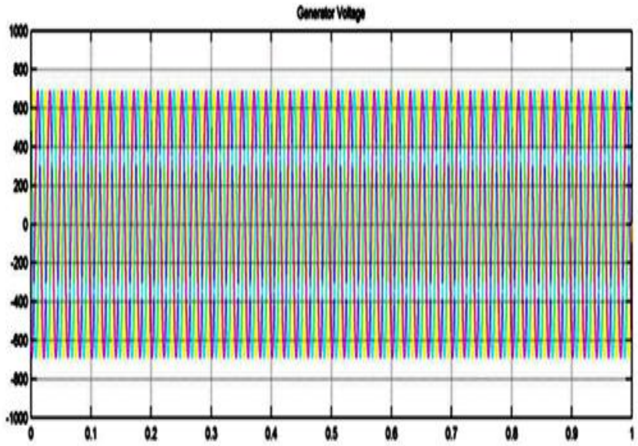


Fig. 8: Generator voltage

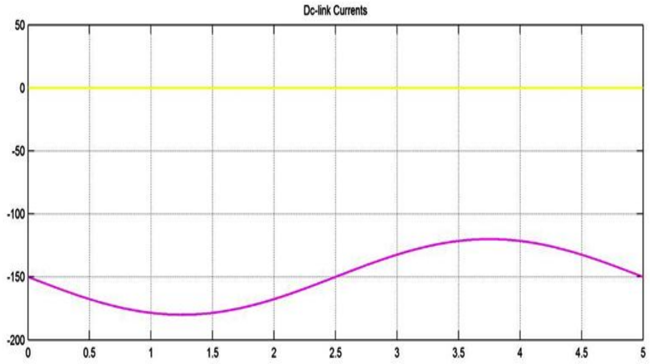


Fig. 9: dc-link currents

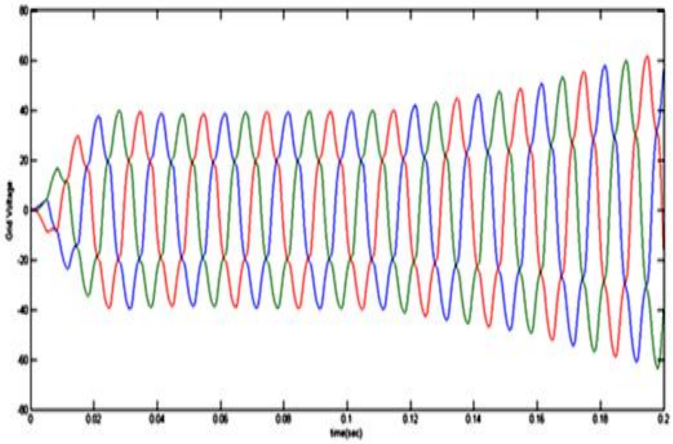


Fig. 10: PID controlled Grid output voltage

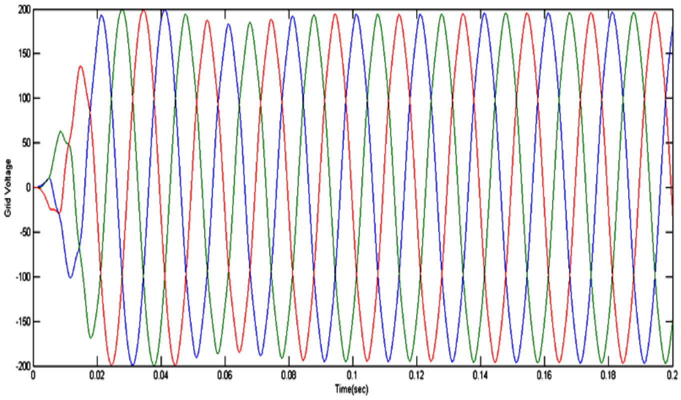


Fig. 11: Fuzzy controlled Grid Voltage

5 Conclusion

The direct integration scheme for supercapacitor bank reduces the power losses, cost, and complexity of the system. Thus, in this paper, the popular dual inverter topology was improved to connect a supercapacitor bank directly into the dc link of the auxiliary inverter and the switching control is implemented using PID and fuzzy controller. The resultant waveforms in Fig. 10 and Fig. 11 show that the fuzzy controller is more effective than the conventional PID controller.

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