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Control System for Producing Electricity with Dual Stator Winding Cage-Rotor Induction Generator

This paper will present the key design equations and control design model of the Dual Stator Winding Cage-Rotor Induction Generator (DSWIG) to achieve wide-speed-range operation with reduced capacity of the static power controller for low power wind or hydro applications. The proposed induction generator consists of a standard squirrel-cage rotor and a stator with two separate windings wound for a similar number of poles. Moreover, the system control strategy using the stator flux orientation is consequently proposed. The aim of the paper is to emphasize that the low speed induction generators with power electronic converters represent a realistic and useful solution for direct drive power applications.

Keywords: dual stator winding, induction generator, active rectifier (inverter), control design, low speed.

1. Introduction

Induction generators have been employed to operate as wind turbine generators and small hydroelectric generators in isolated power systems [1]-[3], due to the practical advantages related to low maintenance cost, better transient performance, ability to operate without dc power supply for field excitation, and brushless construction. With the development of the packaged high speed gas turbine and high speed diesel engine, it becomes increasingly awkward that the prime mover and the generator are connected by a gear reducer. On the contrary, a direct connection between the prime mover and the generator has many advantages, such as low noise, high efficiency, and high power density.

The research in this domain is apparently reorienting, from permanent magnet synchronous generators (PMSG) towards the three-phase/multi-phase/single-phase multi-winding stator, squirrel cage rotor induction generators, chiefly dual-stator generators, to overcome the drawbacks of named synchronous generators, namely [6]-[9]:

- difficulties to obtain magnetic induction sinusoidal distribution along the machine air gap and, consequently, the appearance of voltage and current distortions, that determine increase losses and efficiency decrease;
- construction difficulties and low safety level insertion technology of PMSG;
- cogging torque, that complicates the start up of generator sets (e.g. in the case of unregulated blades wind generators);
- demagnetization risk due to thermal phenomenon determined by Foucault currents in the poles material;
- high cost of a large number of poles of low rated rotation speed generators;

As a competent choice, the cage-type induction generator has many advantages, such as inherent brushless construction, low maintenance demands, and good overload protection ability [4], [5]. For traditional induction generator systems, the major drawbacks are the difficulty of excitation reactive power regulation and the poor output voltage performance under the variations of load and speed, which limit their widespread applications. In a split-wound machine, the stator winding consists of two similar but separate three-phase windings wound for the same number of poles. Both stators are fed with the same frequency and the rotor is a standard squirrel cage. The two stator windings are mutually coupled and small unbalances in the supplied voltages generate circulating currents [6]. In recent years, with the advancement in power electronics and motor control theory, many schemes have been proposed to solve the above problems [4]-[6]. Connecting a dc-ac voltage-source inverter in parallel or series with the loads to provide variable excitation reactive power has facilitated the control of induction generator systems [6]-[8], but these schemes have simultaneously injected harmonics into the load currents and induced the output voltage ripples.

The paper is organized as follows: Section 2: control model, Section 3: control strategy for self excitation case, Section 4: control strategy for grid connection case, Section 5: conclusions.

2. Control model

Figure 1 present the proposed power generation system which have an active rectifier in the main winding and direct connected capacitances in excitation winding. In the proposed scheme the power electronics (active rectifier) is placed in the main windings while in the equivalent variable capacitor, [13] it is used on the excitation winding. The main advantage of active rectifier is the induction generator voltage boosting at low speed while with equivalent variable capacitor this is not possible.

The voltage are [15]:

$$\frac{d\cdot_{d}}{dt} = V_d - R_s \cdot i_d + \mu_b \cdot_{q} \quad , \tag{1}$$

$$\frac{d\cdot_{q}}{dt} = V_q - R_s \cdot i_q + \mu_b \cdot_{d} \quad , \tag{2}$$

$$\frac{d\cdot_{dr}}{dt} = V_{dr} - R_r \cdot i_{dr} + \left(\mu_b - \mu_r\right)\cdot_{qr} \quad , \tag{3}$$

$$\frac{d\cdot_{qr}}{dt} = V_{qr} - R_r \cdot i_{qr} - \left(\mu_b - \mu_r\right)\cdot_{dr} \quad . \tag{4}$$

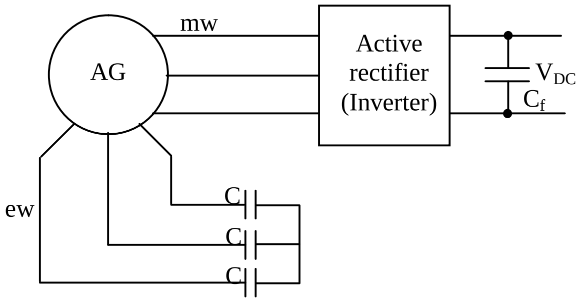


Figure 1. Dual stator winding induction generator with a rectifier (proposed scheme).

From this equations and from phase diagram (figure 2) we have:

$$\cdot_{ed} = \frac{2}{3}\left[\cdot_{Ae}\cdot cos\left(^{-}\right) + \cdot_{Be}\cdot cos\left(^{-} - \frac{2®}{3}\right) + \left(\cdot_{Ce}\cdot cos\left(^{-} + \frac{2®}{3}\right)\right)\right] \quad , \tag{5}$$

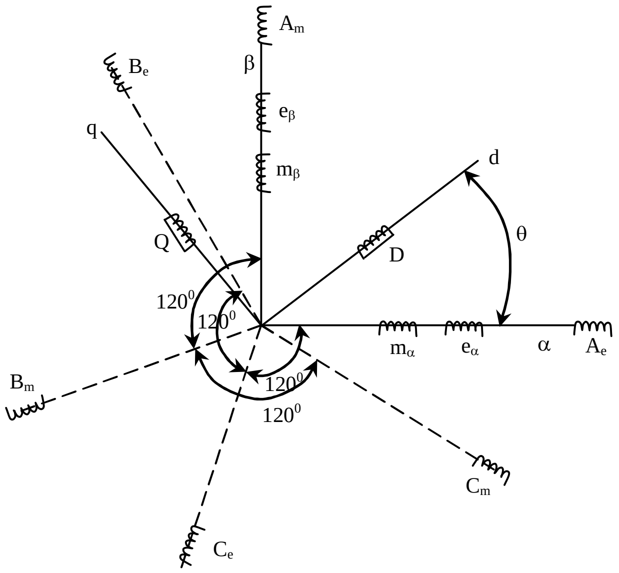


Figure 2. Main, excitation, d-q and α-β winding diagram.

$$\cdot_{eq} = \frac{2}{3}\left[-\cdot_{Ae}\cdot sin\left(\text{¯}\right) - \cdot_{Be}\cdot sin\left(\text{¯} - \frac{2\text{®}}{3}\right) - \cdot_{Ce}\cdot sin\left(\text{¯} + \frac{2\text{®}}{3}\right)\right], \qquad (6)$$

$$\cdot_{md} = \frac{2}{3}\left[\cdot_{Am}\cdot sin\left(\text{¯}\right) + \cdot_{Bm}\cdot sin\left(\text{¯} - \frac{2\text{®}}{3}\right) + \cdot_{Cm}\cdot sin\left(\text{¯} + \frac{2\text{®}}{3}\right)\right], \qquad (7)$$

$$\cdot_{mq} = \frac{2}{3}\left[\cdot_{Am}\cdot cos\left(\text{¯}\right) + \cdot_{Bm}\cdot cos\left(\text{¯} - \frac{2\text{®}}{3}\right) + \cdot_{Cm}\cdot cos\left(\text{¯} + \frac{2\text{®}}{3}\right)\right]. \qquad (8)$$

Analog results the equations for curents (I_{ed}, I_{eq}, I_{md}, I_{mq}) and voltages (U_{ed}, U_{eq}, U_{md}, U_{mq}). For $\theta = 0$ the α, β model is equal with d, q model.

$$\begin{cases} \cdot_{e\sim} = \frac{2}{3}\left(\cdot_{Ae} - \frac{1}{2}\cdot_{Be} - \frac{1}{2}\cdot_{Ce}\right) \\ \cdot_{e} = \frac{2}{3}\left(\frac{\sqrt{3}}{2}\cdot_{Be} - \frac{\sqrt{3}}{2}\cdot_{Ce}\right) \end{cases}, \qquad (9)$$

$$\begin{cases} \cdot_{m\sim} = \frac{2}{3}\left(-\frac{\sqrt{3}}{2}\cdot_{Bm} + \frac{\sqrt{3}}{2}\cdot_{Cm}\right) \\ \cdot_{m} = \frac{2}{3}\left(\cdot_{Am} - \frac{1}{2}\cdot_{Bm} - \frac{1}{2}\cdot_{Cm}\right) \end{cases}. \qquad (10)$$

Magnetic core saturation is very important for induction generator with capacitor excitation because otherwise the system is unstable. Further, deep saturation occurs when a variable speed induction generator with capacitor reactive power compensation is used so the induction generator mathematical model should consider the saturation through an analytical approximation. An analytical continuous and differentiable function, $L_M(i_0)$, is a good approximation for magnetization inductions, for a large current range, only if the following affirmations are true: the function is positive, the magnetic flux is finite (an additional constant term could consider slowly flux increase at very large current), the transient induction L_{Mt} is positive, and the functions L_M and L_{Mt} could have a single maximum when the current are increasing from zero to infinity.

$$L_M = f\left[\left(i_{md} + i_{ed} + i_D\right)^2 + \left(i_{mq} + i_{eq} + i_Q\right)^2\right], \qquad (11)$$

$$\begin{pmatrix} \cdot_{md} \\ \cdot_{ed} \\ \cdot_{D} \end{pmatrix} = \begin{pmatrix} L_M + L_{me\pm} + L_{m\pm} & L_M + L_{me\pm} & L_M \\ L_M + L_{me\pm} & L_M + L_{me\pm} + L_{e\pm} & L_M \\ L_M & L_M & L_M + L_{r\pm} \end{pmatrix} \cdot \begin{pmatrix} i_{md} \\ i_{ed} \\ i_D \end{pmatrix}, \qquad (12)$$

$$\begin{pmatrix} \cdot_{mq} \\ \cdot_{eq} \\ \cdot_{Q} \end{pmatrix} = \begin{pmatrix} L_M + L_{me\pm} + L_{m\pm} & L_M + L_{me\pm} & L_M \\ L_M + L_{me\pm} & L_M + L_{me\pm} + L_{e\pm} & L_M \\ L_M & L_M & L_M + L_{r\pm} \end{pmatrix} \cdot \begin{pmatrix} i_{mq} \\ i_{eq} \\ i_Q \end{pmatrix}, \qquad (13)$$

$$\cdot_{m\sim} = L_M + \left(i_{s\sim} + i_{r\sim}\right) + \cdot_R\, cos\left(\text{¯}\right), \qquad (14)$$

$$i_{0\sim} = i_{s\sim} + i_{r\sim} \quad , \tag{15}$$

$$\cdot_{m} = L_M + \left(i_s + i_r\right) + \cdot_{R} \sin\left(\bar{\ }\right) \ , \tag{16}$$

$$i_0 = i_s + i_r \quad , \tag{17}$$

From dependence:

$$L_M = f\left(i_0\right) > 0 \quad , \tag{18}$$

where i_0 is the magnetization current and $L_M\left(i_0\right) \cdot i_0$ is bounded $\forall i_0 \geq 0$:

$$i_0 = \sqrt{\left(i_{md} + i_{ed} + i_D\right)^2 + \left(i_{mq} + i_{eq} + i_Q\right)^2} \quad , \tag{19}$$

the transitory magnetization inductance is:

$$L_{Mt} = \frac{\partial L_M}{\partial i_0} \cdot i_0 + L_M > 0 \quad . \tag{20}$$

With notation:

$$A = \begin{pmatrix} L_{Mt} + L_{me\pm} + L_{m\pm} & L_{Mt} + L_{me\pm} & L_{Mt} \\ L_{Mt} + L_{me\pm} & L_{Mt} + L_{me\pm} + L_{e\pm} & L_{Mt} \\ L_{Mt} & L_{Mt} & L_{Mt} + L_{r\pm} \end{pmatrix} , \tag{21}$$

$$A = L_{Mt} \cdot I_3 + \begin{pmatrix} L_{me\pm} + L_{m\pm} & L_{me\pm} & 0 \\ L_{me\pm} & L_{me\pm} + L_{e\pm} & 0 \\ 0 & 0 & L_{r\pm} \end{pmatrix} , \tag{22}$$

$$A = L_{Mt} \cdot I_3 + L_{\pm} \quad , \tag{23}$$

$$A \cdot \begin{pmatrix} \dfrac{di_{md}}{dt} \\ \dfrac{di_{ed}}{dt} \\ \dfrac{di_D}{dt} \end{pmatrix} = \begin{pmatrix} U_{md} & - R_m \cdot i_{md} + \mu_b \cdot {}_{mq} \\ U_{ed} & - R_e \cdot i_{ed} + \mu_b \cdot {}_{eq} \\ 0 & - R_D \cdot i_D + \left(\mu_b - \mu_r\right) \cdot {}_{Q} \end{pmatrix} = C \ , \tag{24}$$

$$A \cdot \begin{pmatrix} \dfrac{di_{mq}}{dt} \\ \dfrac{di_{eq}}{dt} \\ \dfrac{di_Q}{dt} \end{pmatrix} = \begin{pmatrix} U_{mq} & - R_m \cdot i_{mq} - \mu_b \cdot {}_{md} \\ U_{eq} & - R_e \cdot i_{eq} - \mu_b \cdot {}_{ed} \\ 0 & - R_Q \cdot i_Q - \left(\mu_b - \mu_r\right) \cdot {}_{D} \end{pmatrix} = D \ , \tag{25}$$

$$\frac{d}{dt} \begin{pmatrix} i_{md} \\ i_{ed} \\ i_D \end{pmatrix} = A^{-1} \cdot C \quad , \tag{26}$$

$$\frac{d}{dt} \begin{pmatrix} i_{mq} \\ i_{eq} \\ i_Q \end{pmatrix} = A^{-1} \cdot D \quad . \tag{27}$$

The fluxes in rotor ϕ_Q and ϕ_D are:

$$\phi_Q = \begin{pmatrix} L_M & L_M & L_M + L_{r\sigma} \end{pmatrix} \cdot \begin{pmatrix} i_{mq} \\ i_{eq} \\ i_Q \end{pmatrix} , \tag{28}$$

$$\phi_D = \begin{pmatrix} L_M & L_M & L_M + L_{r\sigma} \end{pmatrix} \cdot \begin{pmatrix} i_{md} \\ i_{ed} \\ i_D \end{pmatrix} . \tag{29}$$

The principle of DSWIG control is presented in fig. 3.

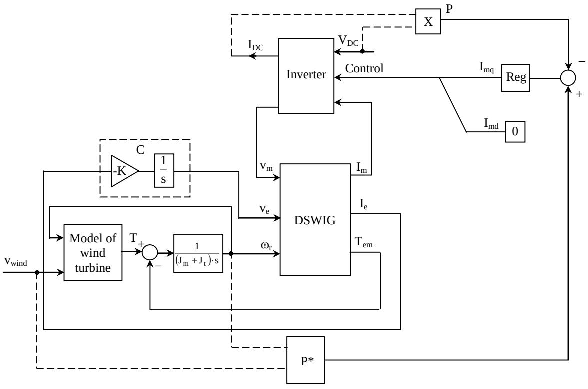


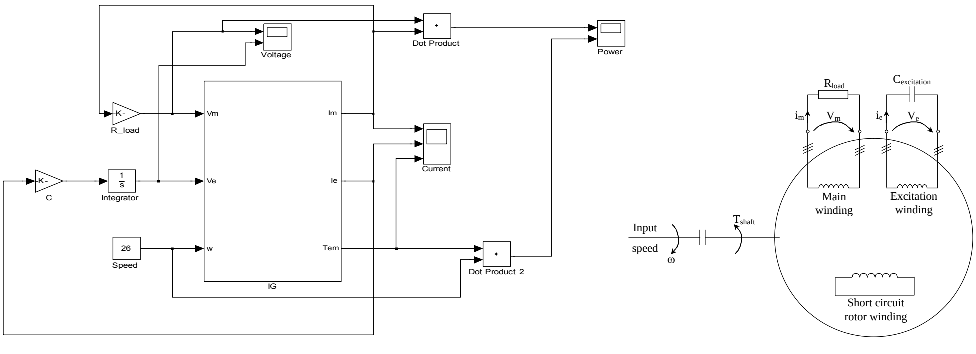
Figure 3. Principle of DSWIG control.

3. Control strategy for self excitation case

Magnetic core saturation is very important for induction generator with capacitor excitation because otherwise the system is unstable. Further, deep saturation occurs when a variable speed induction generator with capacitor reactive power compensation is used so the induction generator mathematical model should consider the saturation through an analytical approximation.

The control strategy for self excitation case is illustrated in fig. 4 via a dedicate Matlab Simulink code and fig. 5 show the Simulink diagram of the DSWIG with saturated model and remanence model implemented.

From the reactive energy balance the capacitor values is C_n=71.5μF. The dynamic models which include the winding losses prove that self excitation starts slowly with a 58 μF capacitor. With the C_n capacitor, self excitation starts at 23.4rad/s. The no-load self excitation process at rated speed and C_n capacitor is shown in fig. 6 (voltages, currents and torque). At time 3.947 s, the generator is sudden charged with the rated load (load resistance is reduced from 4840 Ω to a 48.4 Ω.



a) b)

Figure 4. a) Simulink diagram of the DSWIG drive, self excitation case; b) Block diagram

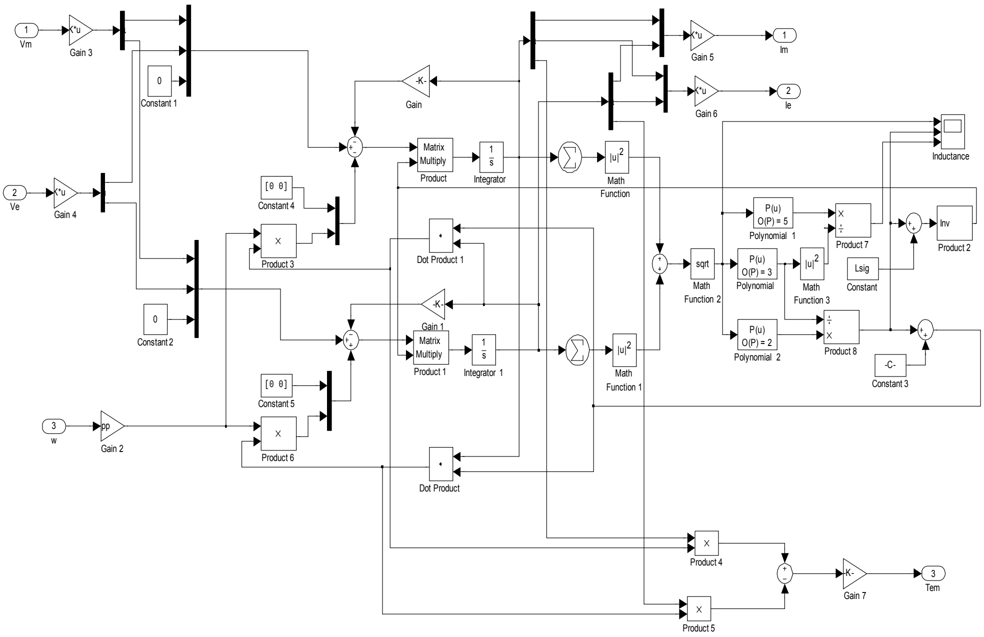


Figure 5. Detailed diagram of the DSWIG with remanence and saturation.

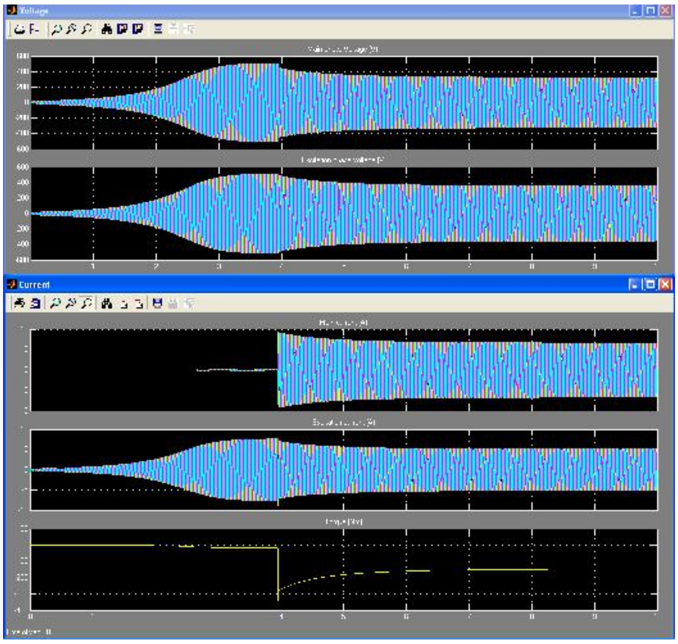
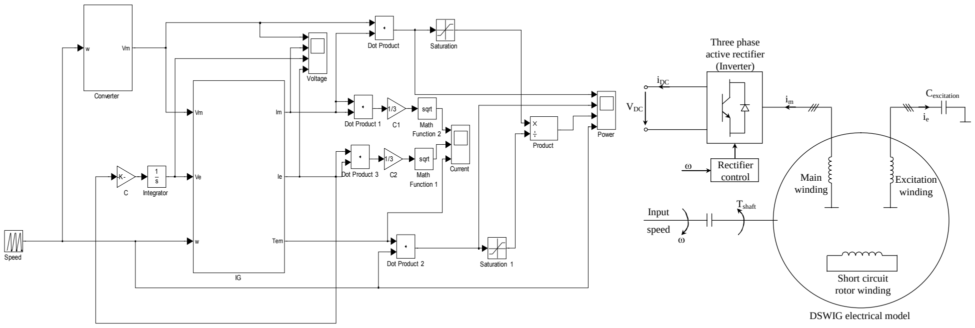


Figure 6. Main phase voltages, excitation phase voltages, main current, excitation current and torque self excitation case.

4. Control strategy for grid connection case

Using a controlled rectifier the speed range will be extended from 12 rad/s to 26rad/s. The controlled rectifier will be used to boost the voltage, to provide the extra magnetization current at low speed. The active power is decreasing with cube of speed, and the torque with square of speed which means the active current trough active rectifier is decreasing and there is possible to introduce a reactive component.



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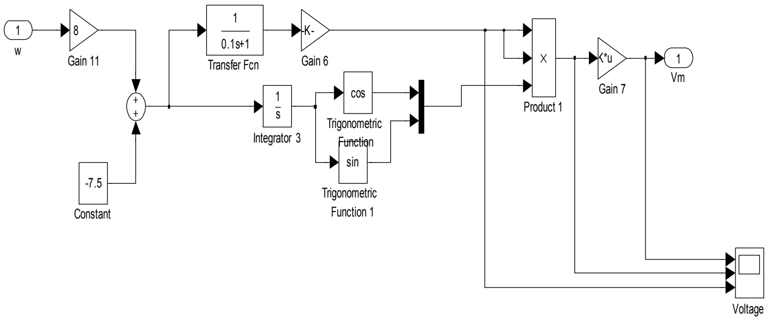

c)

Figure 7. a)Simulink diagram of the DSWIG drive with controlled converter; b) Block diagram; c) converter control.

In this case the control strategy is illustrated in fig. 7 and dynamic simulations are presented in fig. 8, and 9 for speed variation. In figure 10 is presented the original proposed scheme for reduced cost low speed wind or hydro energy conversion system with DSWIG, and in figure 11 dynamic simulations for this case.

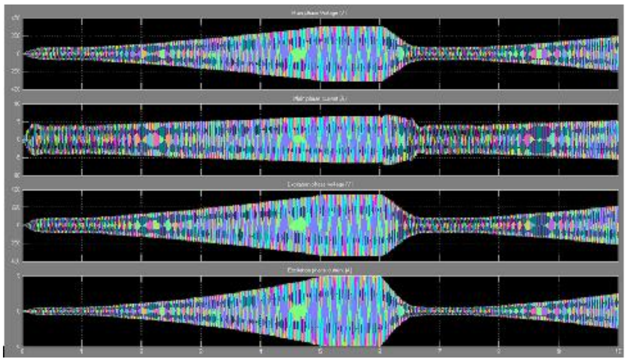

Figure 8. Main and excitation phase voltages, main and excitation phase currents.

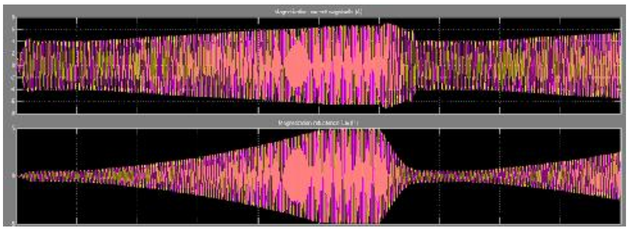

Figure 9. Magnetization current magnitude and magnetization inductance.

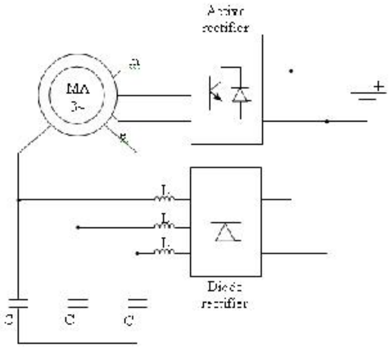

Figure 10. The proposed solution for low speed wind or hydro energy conversion system.

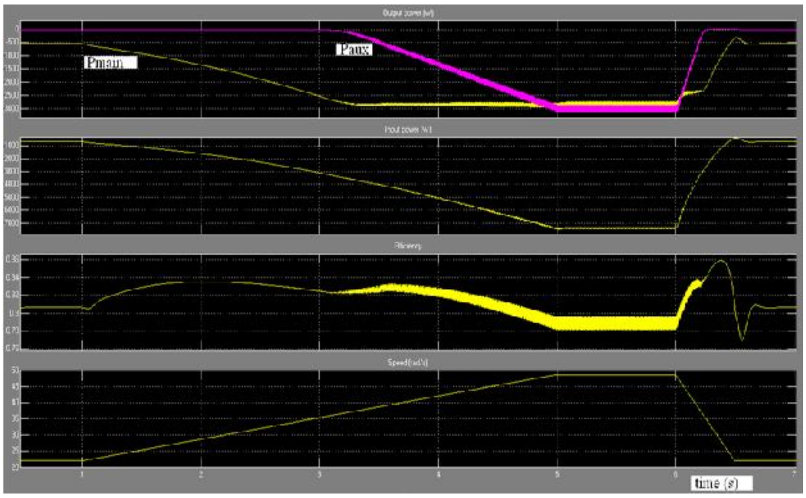

Figure 11. Power and efficiency variation for new proposed solution.

5. Conclusions

In this paper was presented a new type of twin stator windings induction machine operating in generator mode. The main advantage of the TSWIG is its improved capability to operate at variable low speed for wind or hydro power plants.

A mathematical perfectly saturated model should be implemented in flux rotating frame coordinate and then the transients and steady state magnetization inductance could be considered in the model. In our application a long time simulation is required, without fast transients and than a little simplification of the model using stator frame coordinate is used with the lack of using only the steady state magnetization inductance.

In order to reduce the cost a new configuration using a active rectifier for the main stator winding and a diode rectifier for the excitation winding is proposed. The proposed controller reduces the required kVA rating of both converters around 50% (which are even less than that of the machine side converter for a conventional rotor side control configuration), improves the efficiency and helps operating over a wide speed range.

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