VOLTAGE SOURCE INVERTER FOR VOLTAGE AND FREQUENCY CONTROL OF A STAND-ALONE SELF-EXCITED INDUCTION GENERATOR

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Abstract

Frequency and voltage control of a stand-alone induction generator along with a voltage source inverter (VSI) controller to supply the reactive power required for excitation of induction generator is proposed. The VSI-based controller also regulates the generated voltage and frequency by maintaining a constant impedance as observed by the generator. This provides sufficient time to regulate the prime mover. A system model is developed and an experimental setup is built. Results indicate a wide control range and elimination of the three-phase AC capacitor bank. Sever load changes up to 100% are tested with no noticeable change on the voltage or frequency.

Keywords: *Induction generator; renewable energy; VSI.*

1. Introduction

In remote areas, far from main power lines, electric power can be generated by a small stand-alone hydro power plant. In such a situation, the hydro turbine is driven by a steady flow of water along with an induction machine (IM). The IM becomes attractive due to its low cost and ruggedness. The IM can generate AC electric power when driven by a prime mover and injected by reactive power from a bank of AC capacitors. The residual magnetism in the IM rotor produces a small voltage in the stator windings. If a bank of capacitors is connected to the stator winding then a capacitive current flows in the AC capacitors. This resulting current provides a positive feedback that causes a further increase in the voltage. This process is called self-excitation which is eventually limited due to the magnetic saturation of the machine [1]. The voltage and frequency of such an induction generator in stand-alone operation are very sensitive to load changes.

A conventional method for frequency control is shown in Figure 1. As the load power demand changes, the input power into the induction generator (IG) also changes to match the load power demand. A speed governor is employed for the regulation of the prime mover. The speed governor is generally quite expensive and due to its large mechanical time constant, is unable to react fast enough to transients. As a result, the regulation of voltage and frequency has low performance. Furthermore, the voltage and frequency regulation requires a smoothly variable reactive power source.

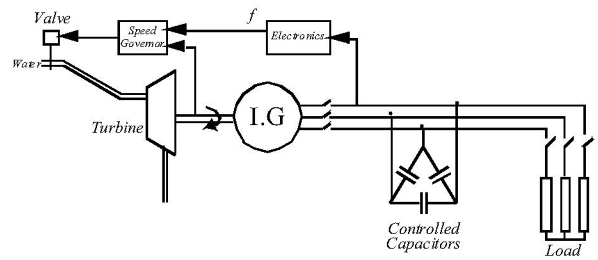

Figure 1. Conventional scheme for prime mover regulation.

Other methods to control the voltage and frequency [2, 3, 4] employ a controller consisting of a phase controlled bridge and a DC-chopper to achieve the regulation. A disadvantage of this approach is a limited control range. This type of controller can supply neither real nor reactive power to the system and hence requires a large AC side capacitor bank for the excitation of the induction generator. Furthermore, the controller is unable, even for a short time, to compensate for fast load transients generated by power surges.

This paper proposes a power controller scheme based on a voltage source inverter. The controller regulates the voltage and frequency as well as provides the reactive power required for excitation of the stand-alone induction generator with squirrel cage rotor. This scheme employs IGBTs with fast protective electronics circuits and offers a robust and reliable controller. The proposed controller provides a wider range of control especially provides necessarily reactive power for excitation and, during transients for a short time, real power.

Section 2 provides overall system description and modeling. Section 3 presents the detailed analysis and modeling of the proposed voltage source inverter (VSI) based controller and section 4 presents the implementation and the experimental results. Conclusions are presented in section 5.

2. System Description

Figure 2 depicts the schematic of the VSI-based controller where AC side is connected in parallel to the load and DC side can be configured in various ways. It can be connected to a general DC source, which is an unrealistic scenario for the intended purpose, but provides insight into the principle of the proposed controller. The DC side consists of an electrolytic DC capacitor and a resistor. Large double layer capacitors can be used that provide short time energy storage (Joules).

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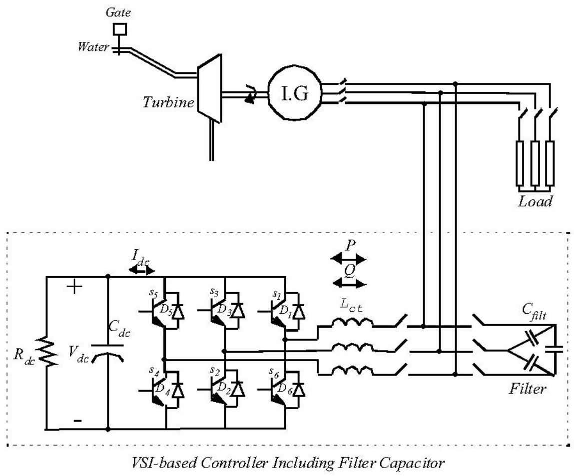

Fig. 2. Schematic of overall generator system.

2.1. Turbine, Induction Generator, and Load

The hydro turbine is considered to deliver a certain constant power to the IG and can be characterized as:

$$T_{sh} = T_0 - M(\Omega - \Omega_0) \quad , \tag{1}$$

where T_0 is any point on the straight line of torque-speed characteristic corresponding to the hydro power and M is the negative gradient of the characteristic.

Figure 3 shows the equivalent circuit for the dynamic behavior of the IG [5]. The differential equations are expressed in the synchronous frame with the generator voltage (V_s) as the reference and are as follows [2]:

$$\frac{d\psi_{sR}}{dt} = v_{sR} - R_s \cdot i_{sR} + \omega \cdot \psi_{sI} \tag{2}$$

$$\frac{d\psi_{sI}}{dt} = -R_s \cdot i_{sI} - \omega \cdot \psi_{sR} \tag{3}$$

$$\frac{d\psi_{rR}}{dt} = -R_{rs} \cdot i_{rR} - (\Omega - \omega) \cdot \psi_{rI} \tag{4}$$

$$\frac{d\psi_{rI}}{dt} = -R_{rs} \cdot i_{rI} + (\Omega - \omega) \cdot \psi_{rR} \tag{5}$$

$$\frac{d\Omega}{dt} = \frac{1}{J}\left[T_0 - M \cdot (\Omega - \Omega_0) - \psi_{rR} \cdot i_{rI} + \psi_{rI} \cdot i_{rR}\right] \tag{6}$$

where R is the real and I the imaginary components.

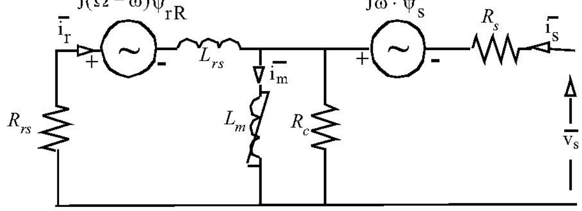

Fig. 3. The dynamic equivalent circuit of the IM [2].

The IG feeds power to a load consisting of a series resistor and an inductor. A source of reactive power that excites the IG and provides the reactive power is modeled as an equivalent capacitor C_{VSI}. The differential equations are expressed as:

$$\frac{di_{lR}}{dt} = \frac{1}{L_l}\left(v_{sR} - R_l \cdot i_{lR}\right) + \omega \cdot i_{lI} \tag{7}$$

$$\frac{di_{lI}}{dt} = -\frac{R_l}{L_l} \cdot i_{lI} - \omega \cdot i_{lR} \tag{8}$$

$$\frac{dv_{sR}}{dt} = \frac{i_{C_{VSI}R}}{C_{VSI}} \tag{9}$$

and one algebraic equation that is expressed as:

$$\omega = \frac{i_{C_{VSI}I}}{C_{VSI} v_{sR}} \tag{10}$$

The steady-state equations are formulated by setting the time derivatives of variables in equations 2 to 9 to zero. This set of steady-state equations defines the combined system including the hydro turbine, IG, *RL* load, and C_{VSI}. The steady-state equivalent equations are as follows:

$$\omega \cdot \psi_{sI} = -V_{sR} + R_s \cdot i_{sR} \tag{11}$$

$$\omega \cdot \psi_{sR} = -R_s \cdot i_{sI} \tag{12}$$

$$\omega \cdot \psi_{rR} = \frac{\omega}{\Omega - \omega} \cdot R_{rs} \cdot i_{rI} \tag{13}$$

$$\omega \cdot \psi_{rI} = \frac{\omega}{\Omega - \omega} \cdot R_{rs} \cdot i_{rR} \tag{14}$$

$$T_0 - m(\Omega - \Omega_0) = \psi_{rR} \cdot i_{rI} - \psi_{rI} \cdot i_{rR} \tag{15}$$

$$i_{C_{VSI}R} = 0 \tag{16}$$

$$v_{sR} = R_l \cdot i_{lR} - \omega \cdot L_l \cdot i_{lI} \tag{17}$$

$$i_{lI} = -\frac{\omega \cdot L_l}{R_l} \cdot i_{lR} \tag{18}$$

2.2. Reactive Power

The reactive power required for excitation of the IG can be computed under steady-state operation by considering C_{VSI}. C_{VSI} represents the equivalent steady-state capacitance of the VSI-based controller. The reactive power for full (Q_{gen}) and no load (Q_{gen0}) are provided below:

$$Q_{gen0} = \frac{V_s^2}{x_{C_{VSI}}} \tag{19}$$

$$Q_{gen} = \sqrt{V_{s,rated}^2 \cdot I_{s,rated}^2 - P_{rated}^2} \tag{20}$$

3. Voltage Source Inverter Based Controller

This section investigates dynamic and steady-state behavior of the controller.

3.1. Controller Analysis

The characteristic of the excitation capacitors is emulated by the controller that injects reactive power into the IG for generation of real power. The controller is capable of delivering or receiving reactive and real power independently. Figure 5 shows the circuit of a VSI-based controller including the inductor (L_{ct}), a parasitic resister (R_{ct}), the DC capacitor (C_{dc}), and the DC side resistor (R_{dc}). The controller unit is connected to a three-phase star connected voltage source and the terminal voltage of the VSI is synchronized to the source voltage by the gating controller of the VSI [6].

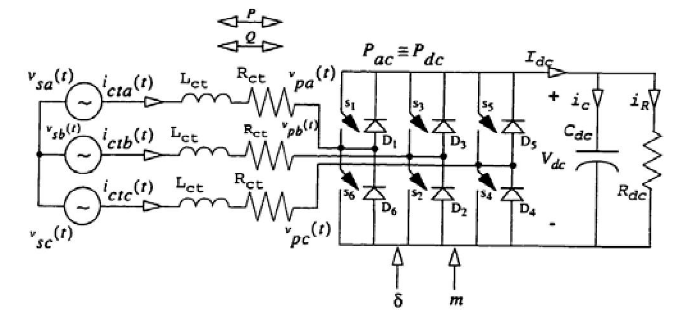

Fig. 5. The VSI-based controller.

Considering the fundamental components, the transient behavior of the VSI-based controller can be determined as:

$$\begin{pmatrix} V_{sa}(t) \\ V_{sb}(t) \\ V_{sc}(t) \end{pmatrix} = V_s \cdot \cos\begin{pmatrix} \omega\cdot t \\ \omega\cdot t - \dfrac{2\pi}{3} \\ \omega\cdot t - \dfrac{4\pi}{3} \end{pmatrix} \tag{21}$$

and

$$\begin{pmatrix} v_{pa}(t) \\ v_{pb}(t) \\ v_{pc}(t) \end{pmatrix} = V_p \cdot \cos\begin{pmatrix} \omega\cdot t + \delta \\ \omega\cdot t + \delta - \dfrac{2\pi}{3} \\ \omega\cdot t + \delta - \dfrac{4\pi}{3} \end{pmatrix} \tag{22}$$

where the reference is chosen as:

$$\overline{V}_s = V_s \angle 0 \quad \text{and} \quad \overline{V}_s = V_s \angle \delta$$

Assuming $P_{ac} = P_{dc}$ as given below:

$$P_{dc} = V_{dc}\cdot i_c + V_{dc}\cdot i_R = V_{dc}\cdot C_{dc}\cdot \frac{dV_{dc}}{dt} + \frac{V_{dc}^{\,2}}{R_{dc}} \quad , \tag{23}$$

and

$$P_{ac} = v_{pa}\cdot i_{cta} + v_{pb}\cdot i_{ctb} + v_{pc}\cdot i_{ctc} \quad , \tag{24}$$

where

$$i_R = \frac{V_{dc}}{R_{dc}} \quad . \tag{25}$$

Considering equations (23)-(24) and the controller currents in synchronous frame results in a set of differential equations describing the dynamics of the system as given below:

$$\begin{pmatrix} \dfrac{di_{ctd}}{dt} \\ \dfrac{di_{ctq}}{dt} \\ \dfrac{dV_{dc}}{dt} \end{pmatrix} = \begin{pmatrix} -\dfrac{R_{ct}}{L_{ct}} & \omega & -\dfrac{k\cdot m}{L_{ct}}\cos\delta \\ -\omega & -\dfrac{R_{ct}}{L_{ct}} & -\dfrac{k\cdot m}{L_{ct}}\sin\delta \\ \dfrac{k\cdot m}{C_{dc}}\cos\delta & \dfrac{k\cdot m}{C_{dc}}\sin\delta & -\dfrac{1}{C_{dc}\cdot R_{dc}} \end{pmatrix} \cdot \begin{pmatrix} i_{ctd} \\ i_{ctq} \\ V_{dc} \end{pmatrix} + \begin{pmatrix} \dfrac{v_{sd}}{L_{ct}} \\ \dfrac{v_{sq}}{L_{ct}} \\ 0 \end{pmatrix} \tag{26}$$

The steady-state operation can be obtained by equating the time derivatives of the variables in (26) to zero, hence:

$$\begin{pmatrix} v_{pd} \\ v_{pq} \\ V_{dc} \end{pmatrix} = \begin{pmatrix} -R_{ct} & \omega\cdot L_{ct} & v_{sd} \\ -\omega\cdot L_{ct} & -R_{ct} & v_{sq} \\ k\cdot m\cdot R_{dc}\cdot\cos\delta & k\cdot m\cdot R_{dc}\cdot\sin\delta & 0 \end{pmatrix} \cdot \begin{pmatrix} i_{ctd} \\ i_{ctq} \\ 1 \end{pmatrix} \tag{27}$$

The real and reactive powers in the synchronous frame are:

$$\begin{pmatrix} P_{ct} \\ Q_{ct} \end{pmatrix} = \begin{pmatrix} v_{sd} & v_{sq} \\ v_{sq} & -v_{sd} \end{pmatrix} \cdot \begin{pmatrix} i_{ctd} \\ i_{ctq} \end{pmatrix} \quad . \tag{28}$$

4. Experimental Setup

A DC machine emulates the prime mover and an induction machine is used as the IG. A series RL load parallel with the controller is connected to the terminals of the IG. A VSI connected to a DC capacitor, and a resistor on the DC side as well as capacitor on the AC side configures the VSI-based controller. This AC capacitor has small capacitance which together with the controller inductance (L_{ct}) forms a filter that attenuates higher order harmonics. Figure 6 shows the experimental setup.

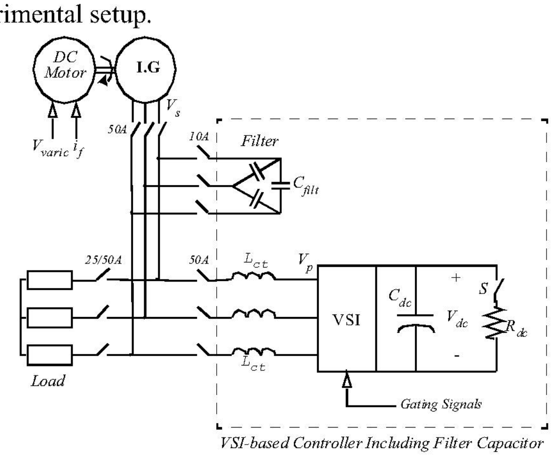

Fig. 6. The experimental setup.

4.1. Results

During the experiment the voltage and frequency of the self-excited IG is controlled only with a feed-forward controller. The steady-state error can be eliminated by employing a feedback controller. Some of the results are presented as follows.

The maximum real power generated is delivered to a load resistance of 2 per unit. The load is suddenly disconnected from the generator system, hence, the generated real power is directed to be consumed in R_{dc}. Figure 7 shows the result where no noticeable transient appear in the voltage (V_s), frequency (f), or generator current (i_s). Figure 8 shows the components of the load in the synchronous frame and the controller current. The instantaneous controller and the load currents are shown in Figure 9.

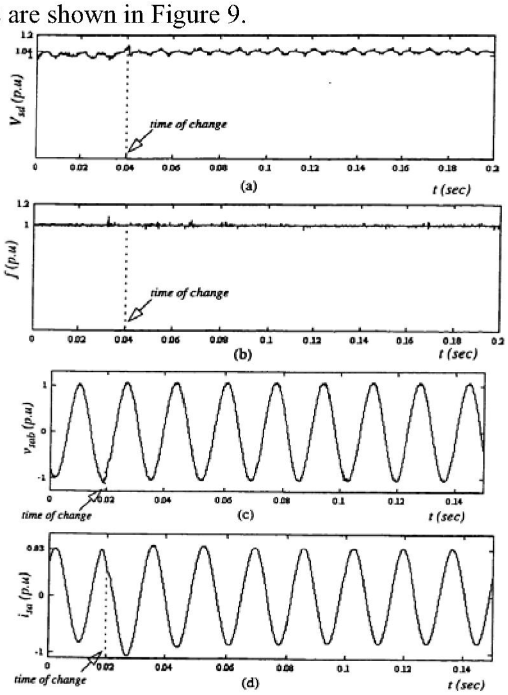

Fig. 7. A 100% load change: *(a)* voltage, *(b)* frequency, *(c)* instantaneous voltage, and *(d)* instantaneous current.

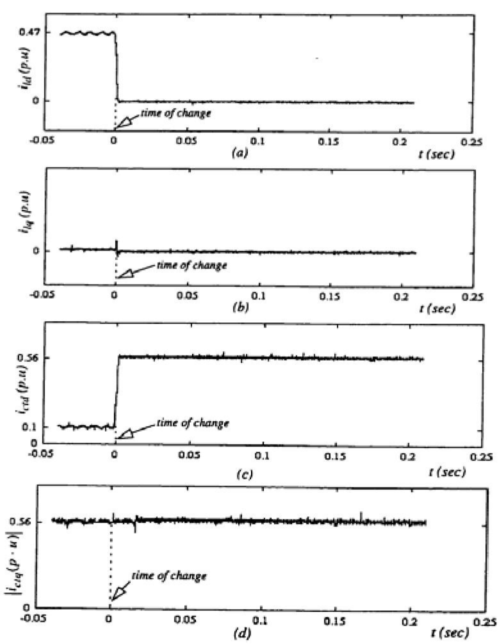

Fig. 8. A 100% load change: *(a)* real, *(b)* reactive of the load currents, *(c)* real, and *(d)* reactive controller currents.

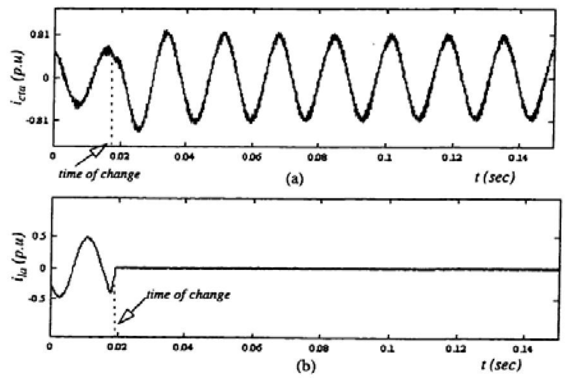

Fig. 9. A 100% load change: *(a)* instantaneous controller current, and *(b)* instantaneous load current.

5. Conclusions

The feasibility of employing a voltage source inverter (VSI) to control the flow of real and reactive power in a stand-alone induction generator plant is investigated. The VSI-based controller will maintain the impedance observed by the induction generator at a constant value. Hence, regulation of the prime mover is not required.

The differential equations developed describe the behavior of the VSI controller and predict the dynamic and steady-state performance of the controller. The overall system has been verified experimentally. The results indicate no noticeable variations in voltage or frequency supplied to the load during load variations.

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