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A simple passive voltage-balancing scheme for three-phase induction generators interfaced with single-phase grids in micro hydroelectric systems

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ABSTRACT

This paper proposes a simple, passive, voltage-balancing scheme for induction generators directly interfaced with single-phase utility grids. The proposed scheme employs two capacitors for balancing the stator voltage and is insensitive to the machine's slip. The paper presents the mathematical analysis and an algorithm for the calculation of the two capacitances. Further, the effectiveness of the proposed scheme is demonstrated through the simulation studies in the PSCAD/EMTDC software environment.

Introduction

Micro hydroelectric technology is clean and well-suited for electrification of remote communities using small water control structures. In many countries, there is a great potential for micro hydroelectric generators in rural areas. For instance, there are more than 10,000 low-head dams and hydraulic structures in Canada [1]. This potential indicates the need for a more in-depth analysis and understanding of micro hydroelectric generators, for higher efficiency and better performance.

Most micro hydroelectric generating systems consist essentially of a turbine and a three-phase induction machine. The machine, however, may be connected to a single-phase power line, as the only available utility grid in most remote areas. Thus, this paper concentrates on the connection of the three-phase induction machine to a single-phase power supply.

The subject matter has been extensively discussed in the literature [2–7], with the main goal having been to provide a balanced three-phase excitation for the stator windings of the machine.

The most widely adopted voltage-balancing technique is to connect a capacitor, referred hereafter to as the voltage-balancing capacitor, across two of the stator terminals [2]. It can be shown that the most balanced three-phase voltage is achieved with a unique capacitance, referred (in [2]) to as the optimum capacitance. Based on the aforementioned approach, however, the voltage balance depends on the slip. Consequently, even with the optimum capacitance, the voltage balance and, therefore, the efficiency of the machine deteriorate as the shaft speed deviates from its nominal value. Reference [3] proposes the use of two capacitors, one for the start-up period and the other one for the normal operation. Thus, the first (start-up) capacitor gets switched to the second (running) capacitor once the shaft speed reaches about 0.8 pu. However, this strategy is optimal at only two speeds (i.e., zero and nominal speeds). Moreover, the sudden switchings of the two capacitors cause undesirable transients. Reference [4] advances the method proposed in [3] by introducing a two-element voltage balancer which uses a capacitor and an inductor. However, the optimum values of capacitance and inductance depend on the slip. Therefore, the method requires two sets of elements, one for the start-up period and the other one for the normal operation. In a slightly different approach proposed by reference [5], the optimum speed at which the switching of the elements should take place is predicted. References [6,7] propose an electronically interfaced capacitor whose effective capacitance may be varied by the duty cycle of an electronic switch. Hence, the stator voltage imbalance can be minimized irrespective of the slip. This strategy, however,

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calls for additional hardware, for both speed measurement and electronic adjustment of the capacitance, which adds to the system complexity and cost.

This paper proposes a simple, passive, voltage-balancing scheme, referred hereafter to as the C-nC configuration, for an induction generator that avoids the aforementioned shortcomings. The proposed scheme minimizes the stator voltage imbalance and, thus, maximizes the efficiency. The proposed configuration employs two fixed capacitors whose capacitances are calculated such that the stator voltage imbalance is minimum and invariant to the slip. The effectiveness of the proposed configuration is demonstrated through simulations conducted in PSCAD/EMTDC software environment.

C configuration

Fig. 1 shows the schematic diagram of a micro hydroelectric system. As Fig. 1 shows, the system consists of a water turbine, an archimedes screw in this case, which produces mechanical torque from the running water, a step-up gearbox, and a three-phase induction generator which is directly interfaced with a host electric grid. The system is desirable to produce the largest possible electrical power at a given water flow. To this end, the generator should operated with a balanced stator voltage, which is difficult to achieve if the utility grid is of the single-phase type, as in most remote sites.

Fig. 2 shows the most common way of connecting a three-phase induction machine to a single-phase power supply. As Fig. 2 shows, two of the stator terminals are connected to the two power supply lines, while the third stator terminal is connected to one of the other two phases via a "*voltage-balancing*" capacitor [2]. Hereafter, the configuration of Fig. 2 is referred to as the "*C configuration*". In Fig. 2, $\mathbf{V_{sa}}, \mathbf{V_{sb}}$, and $\mathbf{V_{sc}}$ denote the stator phase voltage phasors; $\mathbf{I_{sa}}, \mathbf{I_{sb}}$, and $\mathbf{I_{sc}}$ are the stator current phasors; and $\mathbf{Z}$ is the per-phase impedance between each stator terminal and the (virtual) star common point.

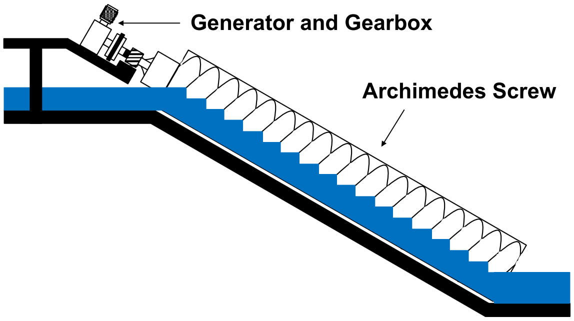

Fig. 1. A micro hydroelectric system based on archimedes screw.

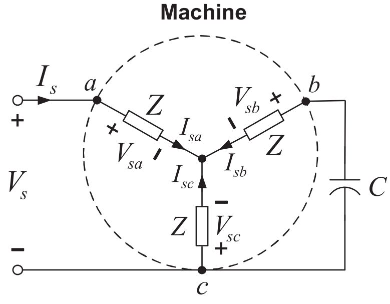

Fig. 2. C configuration.

One can write:

$$\mathbf{V_s} = \mathbf{V_{sa}} - \mathbf{V_{sc}}, \tag{1}$$

$$\mathbf{V_{sb}} = \mathbf{V_{sc}} + jX_c\mathbf{I_{sb}}, \tag{2}$$

where $X_c = 1/(C\omega_s)$, where ω_s is the angular frequency of the power system. The phase voltages can be expressed in terms of their symmetrical components as

$$\begin{bmatrix} \mathbf{V_{sa}} \\ \mathbf{V_{sb}} \\ \mathbf{V_{sc}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{V_{sp}} \\ \mathbf{V_{sn}} \\ \mathbf{V_{s0}} \end{bmatrix}, \tag{3}$$

where $a = e^{j2\pi/3}$. Similarly the stator currents can be expressed in terms of their symmetrical components as

$$\begin{bmatrix} \mathbf{I_{sa}} \\ \mathbf{I_{sb}} \\ \mathbf{I_{sc}} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{I_{sp}} \\ \mathbf{I_{sn}} \\ \mathbf{I_{s0}} \end{bmatrix}. \tag{4}$$

Assuming a three-wire configuration, the zero-sequence components of the stator voltages and currents are zero. However, the positive- and negative-sequence current components are related to the positive- and negative-sequence voltage components as

$$\mathbf{I_{sp}} = \mathbf{Y_p}\mathbf{V_{sp}}, \tag{5}$$

$$\mathbf{I_{sn}} = \mathbf{Y_n}\mathbf{V_{sn}}, \tag{6}$$

where $\mathbf{Y_p}$ and $\mathbf{Y_n}$ are the positive- and negative-sequence admittances seen from the stator terminals. Thus, $\mathbf{Z_p} = \mathbf{Y_p}^{-1}$ and $\mathbf{Z_n} = \mathbf{Y_n}^{-1}$ are the corresponding positive- and negative-sequence impedances, Fig. 3 [2]. In Fig. 3, R_s, X_s, R_r, X_r, X_m, and s are, respectively, the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance, magnetizing reactance, and slip.

Substituting for $\mathbf{V_{sa}}, \mathbf{V_{sb}}, \mathbf{V_{sc}}$, and $\mathbf{I_{sb}}$, from (3) and (4), in (1) and (2), one obtains

$$\mathbf{V_s} = \mathbf{V_{sp}} + \mathbf{V_{sn}} - (a\mathbf{V_{sp}} + a^2\mathbf{V_{sn}}), \tag{7}$$

$$a^2\mathbf{V_{sp}} + a\mathbf{V_{sn}} = a\mathbf{V_{sp}} + a^2\mathbf{V_{sn}} + jX_c(a^2\mathbf{I_{sp}} + a\mathbf{I_{sn}}). \tag{8}$$

In (8), $\mathbf{I_{sp}}$ and $\mathbf{I_{sn}}$ can be expressed in terms of $\mathbf{V_{sp}}$ and $\mathbf{V_{sn}}$ based on (5) and (6):

$$a^2\mathbf{V_{sp}} + a\mathbf{V_{sn}} = a\mathbf{V_{sp}} + a^2\mathbf{V_{sn}} + jX_c(a^2\mathbf{Y_p}\mathbf{V_{sp}} + a\mathbf{Y_n}\mathbf{V_{sn}}). \tag{9}$$

From (7) and (9), $\mathbf{V_{sp}}$ and $\mathbf{V_{sn}}$ are computed as

$$\mathbf{V_{sp}} = \frac{\sqrt{3}j + X_c\mathbf{Y_n}e^{j\pi/6}}{3\sqrt{3}j + \sqrt{3}X_c(\mathbf{Y_n} + \mathbf{Y_p})}\mathbf{V_s}, \tag{10}$$

$$\mathbf{V_{sn}} = \frac{\sqrt{3}j + X_c\mathbf{Y_p}e^{-j\pi/6}}{3\sqrt{3}j + \sqrt{3}X_c(\mathbf{Y_n} + \mathbf{Y_p})}\mathbf{V_s}. \tag{11}$$

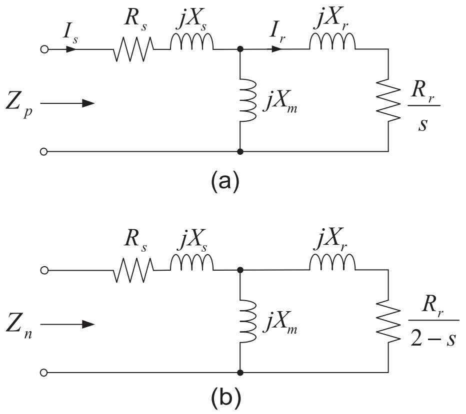

Fig. 3. (a) Positive- and (b) negative-sequence impedances of the machine.