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A proposal for the study of voltage sag in isolated synchronous generators caused by induction motor start-up

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ABSTRACT

This study presents a proposal based on controlled capacitor switching at the moment of three-phase induction motor start-up, when such motors are fed by isolated synchronous generators. This procedure allows for the mitigation of voltage sag that occurs during this transitory period, since a large portion of the reactive power requested during the motor start-up is provided by capacitor banks, thereby relieving a portion of current from the synchronous generator, and with it mitigating the voltage sag. Traditionally, oversizing of the generator was used, under the pretext of mitigating voltage sag. This proposal represents not only an economy, but also power optimization, developed through the motor-generator group, leading to a greater working life.

1. Introduction

Groups of diesel generators are used in a variety of applications when it comes to supplying isolated power loads, for example, to industrial power loads, shopping centers, hospitals, condominiums, among others [1,2]. Whether these be for supplying electric power in an emergency, or for supply at peak demand, the aim is to reduce the cost of electric energy bought from the electric power company.

The diesel generator power group is faced with the task of supplying various load types, among which one finds induction motors. It is known that induction motors demand currents 8–9 times the order of the nominal during start-up, which contain a low power factor [3]. This in turn demands elevated levels of reactive power, and not being able to compensate through the operation of the voltage regulator, voltage sag arises [4–6], or in extreme cases, the synchronous generator is incapable of supplying sufficient power for the start-up of such motors [7].

In a particular installation where the main load is a three-phase induction motor with direct start-up, the generator is scaled to the power function that is demanded by the motor during its start-up. Under such conditions, in order to attend to the motor's apparent power demand, the generator motor group must be scaled up to 8–9 times the motor's power capacity [7]. Consequently, there exists an elevated cost, greater power consumption, as it does not work within the optimized project range. When it comes to diesel motors, the operation using a load less than 30% the nominal, can generate an excessive quantity of unburnt fuel, which will go on to produce an increase in pressure in the next compression stroke. This causes a reduction in the lubrication between the cylinder sleeves and the segment rings, resulting therefore in a repetition of the process, greater wear, which may lead to permanent damage [8–10].

When an induction motor is connected to a bus on an electric system, the effects on its start-up are less severe than when connected to a diesel group containing a synchronous generator, as the reactive power from this generator is extremely limited if compared to that of an electric power network. Noted likewise is the range of devices and methods that support the start-up of induction motors, all of which are aimed at reducing voltage sag, such as the use of frequency inverters, which have brought considerable flexibility to induction motors. However, the application of frequency inverters connected to diesel motor groups for performing induction motor start-up, when the power from the diesel group is close to the motor as is proposed in this article, can contribute to the injection of harmonic currents into the synchronous machine. These currents are in this context, above the levels permitted by

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international standard regulations, and thus are something that will be given detail posteriorly.

In this framework, this study by means of computerized analysis and experimental tests presents a proposal based on capacitor bank controlled switching, using bidirectional solid state switches during the start-up of an induction motor, when connected to an isolated synchronous generator. Results will be shown for both the computerized simulations and the experimental tests of the direct start-up of a 2 hp induction motor, supplied by a 2 kVA synchronous generator, with and without capacitor bank switching, or be it, using the philosophy previously adopted to not oversize the synchronous generator.

2. Transitory behavior of a synchronous generator – sudden change in load

In order to analyze this transitory behavior of a synchronous generator faced with a sudden change in load, the equivalent circuit from the machine of domain $dq0$ is considered and in accordance with Refs. [11–14], one has the following modeling.

$$\begin{bmatrix}\bar{e}_d(\bar{t})\\ \bar{e}_q(\bar{t})\\ \bar{e}_0(\bar{t})\end{bmatrix} = \begin{bmatrix}0 & -\frac{d\theta}{dt} & 0\\ \frac{d\theta}{dt} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}\bar{\psi}_d(\bar{t})\\ \bar{\psi}_q(\bar{t})\\ \bar{\psi}_0(\bar{t})\end{bmatrix} + \begin{bmatrix}\frac{d}{dt}\bar{\psi}_d(\bar{t})\\ \frac{d}{dt}\bar{\psi}_q(\bar{t})\\ \frac{d}{dt}\bar{\psi}_0(\bar{t})\end{bmatrix} - \bar{r}\begin{bmatrix}\bar{i}_d(\bar{t})\\ \bar{i}_q(\bar{t})\\ \bar{i}_0(\bar{t})\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}E_{fd}\\ 0\\ 0\end{bmatrix} = \begin{bmatrix}\frac{d}{dt}\bar{\psi}_{fd}(\bar{t})\\ \frac{d}{dt}\bar{\psi}_{kd}(\bar{t})\\ \frac{d}{dt}\bar{\psi}_{kq}(\bar{t})\end{bmatrix} + \begin{bmatrix}r_{fd}i_{fd}(\bar{t})\\ r_{kd}i_{kd}(\bar{t})\\ r_{kq}i_{kq}(\bar{t})\end{bmatrix} \quad (2)$$

being

$$\begin{bmatrix}\bar{\psi}_d(\bar{t})\\ \bar{\psi}_q(\bar{t})\\ \bar{\psi}_0(\bar{t})\end{bmatrix} = -\begin{bmatrix}\bar{L}_d & 0 & 0\\ 0 & \bar{L}_q & 0\\ 0 & 0 & \bar{L}_0\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_d(\bar{t})\\ \bar{i}_q(\bar{t})\\ \bar{i}_0(\bar{t})\end{bmatrix} + \begin{bmatrix}\bar{L}_{afd} & \bar{L}_{akd} & 0\\ 0 & 0 & \bar{L}_{akq}\\ 0 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_{fd}(\bar{t})\\ \bar{i}_{kd}(\bar{t})\\ \bar{i}_{kq}(\bar{t})\end{bmatrix} \quad (3)$$

$$\begin{bmatrix}\bar{\psi}_{fd}(\bar{t})\\ \bar{\psi}_{kd}(\bar{t})\\ \bar{\psi}_{kq}(\bar{t})\end{bmatrix} = -\frac{3}{2}\begin{bmatrix}\bar{L}_{afd} & 0 & 0\\ \bar{L}_{akd} & 0 & 0\\ 0 & \bar{L}_{akq} & \bar{L}_0\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_d(\bar{t})\\ \bar{i}_q(\bar{t})\\ \bar{i}_0(\bar{t})\end{bmatrix} + \begin{bmatrix}\bar{L}_{ffd} & \bar{L}_{fkd} & 0\\ \bar{L}_{fkd} & \bar{L}_{kkd} & 0\\ 0 & 0 & \bar{L}_{kkq}\end{bmatrix}\cdot\begin{bmatrix}\bar{i}_{fd}(\bar{t})\\ \bar{i}_{kd}(\bar{t})\\ \bar{i}_{kq}(\bar{t})\end{bmatrix} \quad (4)$$

where e_{dq0} is the voltage in the $dq0$ domain; E_{fd} field excitation voltage; ψ_{dq0} flux linkages in $dq0$ domain; ψ_{fd} total flux linkage of d-axis field coil; ψ_{kd} total flux linkage of d-axis damper coil; ψ_{kq} total flux linkage of q-axis damper coil; i_{dq0} currents in the $dq0$ domain; i_{fd} current in d-axis field coil; i_{kd} current in d-axis damper coil; i_{kq} current in q-axis damper coil; r resistance of each stator coil; r_{fd}, r_{fd}, r_{fd} resistance of field d-axis, damper d-axis coil, damper q-axis coil, respectively; L_d, L_q, L_0 are the self-inductances of the stator $dq0$ phase(axis) coils, respectively; L_{afd}, L_{akd}, L_{akq} are the mutual inductance between the phase a stator coil and rotor d-axis coil; L_{ffd}, L_{kkd}, L_{kkq} the self-inductances of each rotor coil; and L_{fkd} and L_{kfd} are the mutual inductance between the rotor d-axis coil and the damper d-axis coil.

Through the adoption of $s\bar{\theta} = \frac{d\theta}{dt}$ in order to facilitate one's understanding of the equation, by deriving Eq. (3) and substituting the result in the second term of Eq. (1), for eliminating the variable flow, one has:

$$\left.\begin{aligned} -(\bar{e}_d + s\bar{\theta}\cdot\bar{\psi}_q) &= \bar{L}_l\cdot s\bar{i}_d + \bar{r}\cdot\bar{i}_d + \bar{L}_{ad}\cdot s(\bar{i}_d - \bar{i}_{fd} - \bar{i}_{kd})\\ -(\bar{e}_q - s\bar{\theta}\cdot\bar{\psi}_d) &= \bar{L}_l\cdot s\bar{i}_q + \bar{r}\cdot\bar{i}_q + \bar{L}_{aq}\cdot s(\bar{i}_q - \bar{i}_{kq})\\ -\bar{e}_0 &= \bar{L}_0\cdot s\bar{i}_0 + \bar{r}\cdot\bar{i}_0 \end{aligned}\right\} \quad (5)$$

where L_{ad} is the stator d-axis inductance due to flux, which does link rotor circuits effectively in the d-axis; L_{aq} the stator q-axis inductance due to flux, which does link rotor circuits effectively in the q-axis; L_l the inductance due to flux which does not link any rotor circuits, in other words the leakage inductance. Being $L_l \equiv L_{\text{leak}\,d} \cong L_{\text{leak}\,q}$.

Through the derivation of Eq. (4) and substituting the result in the second term of Eq. (2), and through mathematic manipulation, one has:

$$\left.\begin{aligned} &\bar{E}_{fd} = \bar{L}_{ad}\cdot s(\bar{i}_d - \bar{i}_{fd} - \bar{i}_{kd}) + (\bar{L}_{fkd} - \bar{L}_{ad})\cdot s(\bar{i}_{fd} + \bar{i}_{kd})\\ &+(\bar{L}_{ffd} - \bar{L}_{fkd})\cdot s\bar{i}_{fd} + \bar{r}_{fd}\cdot\bar{i}_{fd}\\ &0 = \bar{L}_{ad}\cdot s(\bar{i}_d - \bar{i}_{fd} - \bar{i}_{kd}) + (\bar{L}_{fkd} - \bar{L}_{ad})\cdot s(\bar{i}_{fd} + \bar{i}_{kd})\\ &+(\bar{L}_{kkd} - \bar{L}_{fkd})\cdot s\bar{i}_{kd} + \bar{r}_{kd}\cdot\bar{i}_{kd}\\ &0 = \bar{L}_{aq}\cdot s(\bar{i}_q - \bar{i}_{kq}) + (\bar{L}_{kkq} - \bar{L}_{aq})\cdot s\bar{i}_{kq} + \bar{r}_{kq}\cdot\bar{i}_{kq} \end{aligned}\right\} \quad (6)$$

Eqs. (5) and (6) are the unified equations for a generator in the $dq0$ domain, which were obtained from the physical concept of the synchronized machine, these went on to be introduced through a careful mathematical procedure. Furthermore, the precise equivalent circuit of these equations can be designed as shown in Fig. 1, where a circuit for each axis is presented, being that the concatenated flow can be added to the figure as $\bar{\psi} = \bar{L}\cdot\bar{i}$. If necessary, these circuits are electrically interlinked by means of the mutual flow couplings $\bar{\psi}_d$ and $\bar{\psi}_q$.

Through the introduction of the new symbols for the inductances $\bar{L}_{fd}$, $\bar{L}_{kd}$, $\bar{L}_{kq}$, which are defined by the following equations and presented onto the equivalent circuit, one has:

$$\left.\begin{aligned} \bar{L}_{fd} &\equiv \bar{L}_{ffd} - \bar{L}_{ad} = \bar{L}_{ffd} - \bar{L}_{fkd}\\ \bar{L}_{kd} &\equiv \bar{L}_{kkd} - \bar{L}_{ad} = \bar{L}_{kkd} - \bar{L}_{fkd}\\ \bar{L}_{kq} &\equiv \bar{L}_{kkq} - \bar{L}_{aq} \end{aligned}\right\} \quad (7)$$

The relationship between the inductances and reactances in the equations are the same, being that:

$$\bar{L} = \frac{L}{L_{\text{base}}} = \frac{2\pi\cdot f_{\text{base}}\cdot L}{2\pi\cdot f_{\text{base}}\cdot L_{\text{base}}} = \frac{x}{x_{\text{base}}} = \bar{x}$$

By adopting the following initial conditions, one has:

$$s\bar{\theta} = \frac{d\theta}{d\bar{t}} = \frac{\omega}{\omega_{\text{base}}} = 0 \quad (8)$$

$$\frac{d}{d\bar{t}}\bar{\psi}_d(t) = \frac{d}{d\bar{t}}\bar{\psi}_d(t) = \frac{d}{d\bar{t}}\bar{\psi}_d(t) = 0 \quad (9)$$

$$\bar{i}_{kd}(t) = \bar{i}_{kq}(t) = 0 \quad (10)$$