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A SIMPLE EXCITATION CONTROL FOR AN ISOLATED SYNCHRONOUS GENERATOR

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Abstract
This paper shows a very simple method of determining the range of field voltages to be applied to an isolated synchronous generator from no-load to full load while maintaining the rated terminal voltage on the stator terminals. The d-q rotor reference frame equations were used for the calculations and it is shown that values of the field voltages determined follow a simple quadratic relationship that offer a very simple control scheme, dependent on only the stator current.

Keywords: saturated reactances, no-load field voltage, excitation control, synchronous generators

1. Introduction

The commonest generator in use today is the field-excited type. The field excitation can be through brushes for low power generators or brushless for high-power alternators. The field windings which produce the primary dc fluxes are usually placed on the rotor because it has to (in most cases) sustain only a small fraction of the armature current. In situations where the load on the generator changes as is usually the case, the excitation must be adjusted continually to maintain constant voltage supply and control of reactive power.

Several excitation control schemes for synchronous generators have been reported in literature. In [1], a global treatment of excitation control is provided with special emphasis on stabilizing oscillations arising from voltage fluctuations. The report in [2] emphasized on a coordinated scheme for both the excitation and governor control using the machine load angle as input signal. El-Missiry [3] presented a wide range excitation controller by modulating the pulsewidth of the PWM converter for the control of a brushless exciter, No additional control signal was needed to accomplish this. The classical report by Schaefer [4] was concentrated on the var control of a synchronous motor and the study was extended to over-excitation schemes for power factor control of power lines to save for var penalties.

The essence of this paper is to show that analytically, it is easy for generator manufacturers to determine the range of field voltages to be applied to a machine in order to suitably operate the generator under all loading conditions at rated voltages and then design the automatic voltage controller (AVR) around this range. Frequency control and control of voltage fluctuations is beyond the scope of the discussion here as it is usually handled by the appropriate generator governing schemes.

2. Basic analysis

The rotor reference frame steady-state equations of a field-excited synchronous machine modelled with one q-axis, a field and one damper winding in the d-axis is [5]:

$$V_{qs} = I_{qs}R_s + X_{ds}I_{ds} + X_{md}\left(I_{dr} + I_{fr}\right) \quad (1)$$
$$V_{ds} = I_{ds}R_s - X_{qs}I_{qs} + X_{mq}I_{qr} \quad (2)$$
$$V_{fr} = I_{fr}R_{fr} \quad (3)$$

The damper cage voltage equations are not of interest here as only steady-state conditions will be discussed. The output rms current I_S is given by:

$$I_S = \sqrt{I_{qs}^2 + I_{ds}^2} \quad (4)$$

3. No load field voltage

At no load the stator currents $I_{ds} = I_{qs} = 0$, the rotor position with respect to the stator mmf wave is at the d-axis ($V_{ds} = 0$) so, $V_{qs} = V_S$. Under steady-state condition, $I_{qr} = I_{dr} = 0$. This will modify (1) to become:

$$I_{fr} = \frac{V_S}{X_{md}} \quad (5)$$

When (5) is substituted into (3), we have:

$$V_{fr} = \frac{R_{fr}}{X_{md}}V_S \quad (6)$$

Equation (6) shows that the no-load excitation voltage required to maintain rated terminal voltage can be deduced from the ratio of the field winding resistance to the unsaturated value of the d-axis magnetizing reactance [6]. The value of V_{fr} obtained in (6) provides the base no-load condition and will validate other results.

4. Field voltage on load at steady-state

At steady-state, $V_{ds} = -V\sin\delta$ and $V_{qs} = V\cos\delta$ so that (1) and (2) now becomes:

$$V_S cos\delta = I_{qs}R_s + X_{ds}I_{ds} + X_{md}I_{fr} \quad (7)$$
$$V_S sin\delta = X_{qs}I_{qs} - I_{ds}R_s \quad (8)$$

Equations (7) and (8) can be solved for I_{ds} and I_{qs} to yield:

$$I_{ds} = \frac{I_{fr}X_{md}X_{qs} + V_S X_{qs}cos\delta - R_s V_S sin\delta}{R_S^2 + X_{ds}X_{qs}} \quad (9)$$

$$I_{qs} = \frac{R_s V_S cos\delta - I_{fr}X_{md}R_s + V_S X_{ds}sin\delta}{R_S^2 + X_{ds}X_{qs}} \quad (10)$$

When (9) and (10) are substituted into (4), the resulting equation will be quadratic in I_{fr}. When it is solved for I_{fr} and finally substituted into (3), two possible solutions for field voltage V_{fr} will result as (11) (at the bottom of this page). In (11), A is defined as:

$$A = \sqrt{I_S^2\left(R_S^2 + X_{qs}^2\right) - V_S^2 sin^2\delta} \quad (12)$$

The negative part of (11) is practically unreasonable. It should be noted that the values of all reactances now appearing in (11) and (12) are dependent on the values of stator current I_S and not just the unsaturated values.

5. Saturation curve of the machine under study

The machine under study is a 10kVA 2-pole 230V three-phase 50Hz alternator used as a stand-by power supply. The rotor is effectively cylindrical and it is assumed that there is no reluctance path in the rotor magnetic circuit so $X_{ds} = X_{qs}$. If the rotor were to have salient poles, then the dependence of the reactances on the stator current will differ between the d- and the q-axis on account of difference in airgap. The machine d-axis reactance variation from no-load to 20% overload with respect to stator rms current was calculated by finite element software FEMAG® and is as shown in Figure 1. The curve of Figure 1 yields (13) by curve fitting.

$$X_{ds} = 2.2I_S^3 - 5.5I_S^2 + 1.3I_S + 6.4 \quad (13)$$

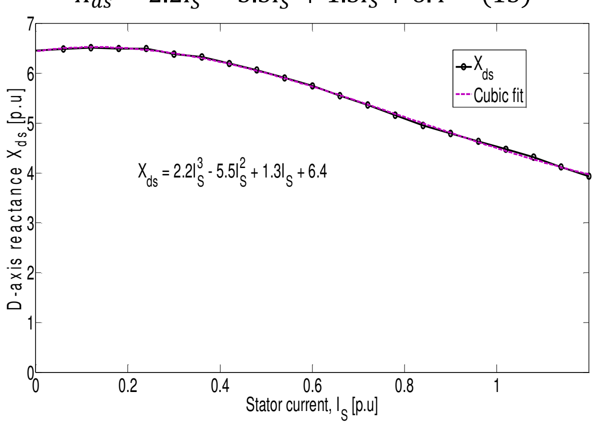

Figure 1: d-axis reactance variation with current

6. The control of excitation

Equation (13) will be used to obtain the variation of the d-axis reactance from no load to full load. Irrespective of the machine rotor type (salient or cylindrical), equation (11) will apply so long as appropriate tables are prepared for the machine reactance variations with stator current. The variation of field voltage according to the positive part of (11) is shown in Figure 2. The excitation control procedure will be to use (13) to obtain X_{ds} for every I_S and then use the values to calculate V_{fr} as per (14).

$$V_{fr} = -0.00012I_S^2 + 0.001I_S + 0.00015 \quad (14)$$

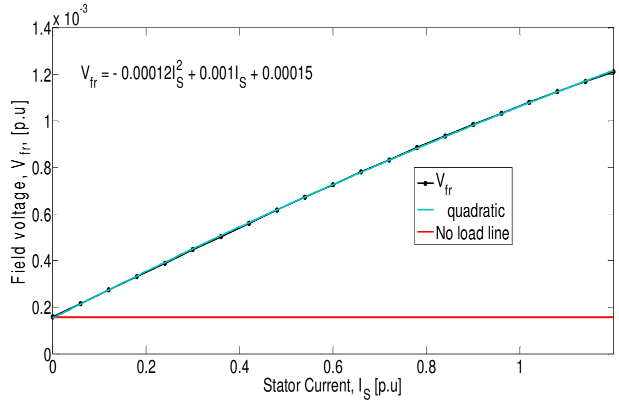

Figure 2: Field voltage control curve

6. Conclusion

The only control variable here is the stator rms current as seen in (13) and (14). The value of field voltage obtained at no load corresponds to the value obtained from section 4 and this validates the results. An AVR design based on the above scheme will only need the load current as the input signal but the control curve given in Figure 2 would have been predetermined from the magnetization curve of the individual machine to be controlled.

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$$V_{fr} = \frac{R_{fr}}{X_{md}}\left(V_S cos\delta \pm \frac{X_{qs}\left(AX_{ds} \mp R_S V_S sin\delta\right) + R_S\left(AR_S \pm V_S X_{d_s} sin\delta\right)}{R_S^2 + X_{qs}^2}\right) \quad (11)$$