OPTIMUM TRADE-OFF OF FLUX SWITCHING GENERATOR AND AC/DC CONVERTER

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ABSTRACT

AC/DC converter is used for the control of the flux-switching machine, derived from a combination of the induction alternator and the switched reluctance machine. There is a trade off between the kVA rating of the generator and that of the converter. This trade off is dependent on the power factor at which the generator is operating. This generator configuration can be controlled to achieve an optimum trade-off of converter and generator kVA depending on requirement. This paper introduces a mathematical model to select the optimum trade-off of converter and generator kVA. Also, it shows that the kVA rating of the converter and the generator can be minimized through control of the power factor of the generator. Finally, the contribution of the developed method is demonstrated in an example taken from previous publications.

I. INTRODUCTION

The growth of embedded generation systems and portable electrical installations has led to the need for the development of low cost, flexible and reliable generation systems. Prime movers used for these generation systems can vary from low speed wind turbine equipment to very high-speed gas turbines.

The wide range of operating speeds for these prime movers mean that no existing generator topology is going to be appropriate for all applications. In order to achieve flexibility, the use of power electronics at the output of generators designed to operate over a very wide speed range is going to be essential.

For very high-speed generator applications, brushless machines have been proposed [1]. These machines include permanent magnet generators (axial and radial flux configurations), switched reluctance generators and designs based on the inductor alternator [1]-[5]. At lower, more conventional speeds the presence of electrical conductors on the rotor makes the synchronous and induction generators remain popular.

Different power factor (PF) correction control techniques have been proposed for AC-to-DC voltage source converters used in power supplies as a measure to improve the poor voltage regulation [6]. Power factor control of a single-phase alternator can be achieved using electronic AC-to-DC converters [6]-[7].

Converter topologies using phase controlled rectifier, and pulse width modulation (PWM) AC-to-DC converter have been used for power factor correction with the latter being widely used, because of the merits of better current waveform shape, good power factor and regeneration ability.

For these PWM converters different control techniques have been proposed to achieve improved power factor for multiple phase applications [8]-[9].

Ref. [10] proposes a PWM controlled single phase, brushless AC, flux-switching generator. The installed kVA of the generator and converter can be minimized through electronic control of the generator power factor over a wide speed range. The output voltage can also be controlled to deliver constant output voltage over a wide speed and power range. This generator is useful in micro turbine applications and as a starter alternator for high-speed turbo-machinery. This flux-switching generator has a field winding on the stator that can be excited separately, and an armature winding also on the stator, which generates the emf, due to the pulsating flux linking it as the machine rotates.

The control of the field excitation introduces one more degree of control for this brushless AC generator. Unlike the permanent magnet brushless generator the excitation can be easily controlled at changing speeds. In safety critical application (such as in fault conditions), the generator voltage can be easily removed, a major advantage over permanent magnet brushless machines for high-speed applications.

This paper introduces a mathematical model to select the optimum trade-off of converter and generator kVA. The major attribute of the method is that it, unlike conventional approaches, guarantees convergence to the optimal solution.

II. FLUX SWITCHING GENERATOR MODEL

The flux-switching generator has a very rugged rotor for high-speed applications. Field current control can be used in the voltage control of this generator.

The generated voltage can also easily be removed in safety critical applications. It is easy to maintain a constant output voltage at increasing speeds without compromising on the power factor level of operation of the generator.

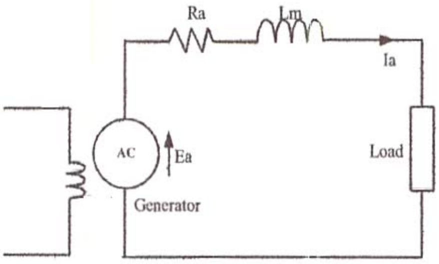

Figure 1. A simplified model of the flux-switching generator with separately excited field circuit

Figure 1 shows a simplified model of the flux-switching generator with separately excited field circuit. An ideal voltage source is in series with the armature inductance and resistance.

This simplified generator model was implemented on Matlab Simulink [10] using the data obtained from the open circuit and short circuit characteristics of the experimental with the aim of establishing if it was sufficiently accurate to form the basis of a more complex model of the AC to DC converter. At high speeds the large synchronous reactance leads to operation at poor power factor. In order to maximize the power output of the generator, operation at high power factor is essential.

Power factor improvement is achieved by injecting reactive power from a reactive power source. This can be done by either using series compensation [4], [7], [9] or fixed capacitance shunt compensation [11].

III. VARIABLE POWER FACTOR PWM AC TO DC CONVERTER EMPLOYING SHUNT COMPENSATION

Figure 2 shows an AC to DC converter proposed for the control of the generator.

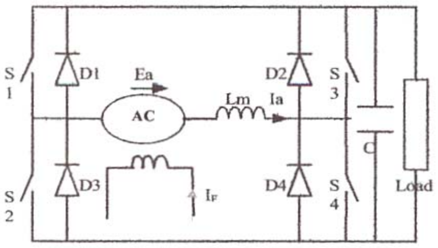

Figure 2. PWM AC/DC converter

The experimental and simulated flux switching motor has been constructed and tested in conjunction with two new power converter circuits [12]-[13].

IV. PER-PHASE MODEL

Figure 3 shows the equivalent per-phase equivalent circuit of the generator.

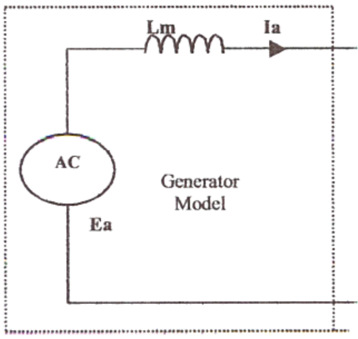

Figure 3. Per –phase equivalent circuit

where V_{ac} is the rms value of the terminal voltage for any given phase angle Φ controlled by the converter, E_a is the back emf of the generator and I_a is the armature current.

The terminal voltage magnitude V_{ac}, for any given phase angle ϕ_g between the generated emf E_a and the armature current I_a, is given by

$$V_{ac} = E_a - I_a * X_{Lm} \quad (1)$$

$$V_{ac} = \sqrt{(E_a - I_a * X_{Lm} * \sin\Phi_g)^2 + (I_a * X_{Lm} * \cos\Phi_g)^2} \quad (2)$$

where

$$X_{Lm} = 2. * \pi * f * Lm \quad (3)$$

is the synchronous reactance at frequency f , and inductance Lm is the armature active inductance, and ϕ_g is the phase angle between the generated emf *Ea* and the armature current *Ia.* Assuming positive ϕ_g means the armature current lags the back emf.

$$V_{ac} = f\,(E_a, I_a, \omega, \phi_g) \tag{4}$$

The output power (P) and apparent power (S_G) of the generator are given according to the equations below

$$P = E_a * I_a * \cos\phi_g \tag{5}$$

$$S_G = E_a * I_a \tag{6}$$

The kVA rating of the converter (S_C) at the output of the generator is given as

$$S_C = V_{ac} * I_a \tag{7}$$

For a generator delivering constant power P, (2) can be rearranged as shown below

$$V_{ac} = \sqrt{\left(E_a - \frac{P * X_{Lm} * \tan\Phi_g}{E_a}\right)^2 + \left(\frac{P * X_{Lm}}{E_a}\right)}^{\,2} \tag{8}$$

From (7) and (8) it can be seen that, while delivering constant power, Vac, and hence S_C can be controlled by varying the back emf, Ea and the phase angle ϕ_g. The best operating point for this generator using this controller occurs at the point for which the trade off between the converter kVA requirement due to V_{ac} and the kVA of the generator is desirable. This occurs at the point where

$$\frac{\partial V_{ac}(E_a, I_a, \omega, \Phi_g)}{\partial(E_a)} = 0. \tag{9}$$

At this point, the controlled AC voltage V_{ac} takes a minimum value. This controlled V_{ac} value directly places a limit on the minimum output DC voltage, and hence the kVA rating on the converter. The converter kVA rating has a direct relationship to the output DC voltage for any given power factor of operation. At this point, the back emf value is given as

$$E_{ao} = \sqrt{\frac{P * X_{Lm}}{\cos\Phi_g}} \tag{10}$$

Also, At this point, the value of the minimum controlled AC voltage is given as V_{ac} (min) is equal to

$$V_{ac}(\min) = \sqrt{\frac{2.*P*X_{Lm}}{\cos\Phi_g}(1.-\sin\Phi_g)} \tag{11}$$

The armature current I_a and the converter rating S_C requirement due to V_{ac}, at E_{ao}, are given as shown in (12) and (13) respectively.

$$I_{ao} = \sqrt{\frac{P}{X_{Lm} * \cos\Phi_g}} \tag{12}$$

$$S_C = \frac{\sqrt{2.*(1.-\sin\Phi_g)}}{\cos\Phi_g} \quad \text{pu} \tag{13}$$

Equation (11) above shows that the magnitude of the controlled voltage V_{ac} for a given output power P depend on the speed of the generator, and the power factor level. Lower V_{ac} voltage values can be achieved by either operating at poor power factor levels, at reduced speed, or by designing a generator with much lower active inductance. From (13) it can be seen that the converter kVA value is independent of speed for operation of the generator at the optimum point. i.e. where (9) is satisfied.

Finally, there is a trade off between the kVA rating of the generator and that of the converter. This trade off is dependent on the power factor at which the generator is operating. This generator configuration can be controlled to achieve an optimum trade-off of converter and generator kVA depending on requirement.

V. SUGGESTED APPROACH FOR OPTIMUM TRDAE-OFF POINT

The approach will be to minimize the difference between the rating of the generator, E_a*I_a, and the converter, $V_{ac}*I_a$.

After formulating the objective function the problem becomes,

$$\text{Find: Ea, } \Phi \text{ to Minimize } (E_a*I_a - V_{ac}*I_a) \tag{14}$$

The Simplex method was chosen due to that it require fewer steps and function evaluations [14]. This simplex method should not be confused with the Simplex method of linear programming.

VI. SIMPLEX SEARCH METHOD

The basic idea in the Simplex method is to compare the values of the objective function at the (n+1) vertices of a general simplex and move the simplex gradually toward the optimum point during the iterative process.

The movement of the simplex is achieved by using three operations, known as reflection, contraction, and expansion.

The points X_1, X_2 and X_3 form the original simplex, and the points X_1, X_2 and X_r form the new one.

At each iteration a new point is generated to replace the worst point, which has the largest function. The new point is obtained from

$$X_r = (1. + \alpha)\, X_o - \alpha\ X_h \quad (15)$$

where
X_o is the initial base point,
X_h is the vertex corresponding ti the maximum function value,
α is the reflection coefficient.

If a reflection produces a new minimum, one can generally expect to decrease the function value further. Hence, one can expand X_r to X_e using the relation

$$X_e = \gamma\ * X_r + (1. - \gamma) * X_o \quad (16)$$

where γ is the expansion coefficient.

If the reflection process gives a point X_r for which

$$f(X_r) > f(X_i) \text{ for all i except i=h,}$$

and

$$f(X_r) < f(X_h),$$

one can replace point X_h by X_r. Thus the new X_h will be X_r. In this case one can contract the simplex as follows

$$X_c = \beta\ * X_h + (1. - \beta) * X_o \quad (17)$$

where β is the contraction coefficient.

The method is assumed to have converged whenever the standard deviation of the function at the (n+1) vertices of the current simplex is smaller than some prescribed small quantity.

This procedure can be continued until the specified convergence is satisfied. When the convergence is satisfied, the centroid X_o of the latest simplex can be taken as the optimum point.

VII. SIMULATED RESULTS AND DISCUSSION

The simulated generator used in Ref. [10] with 12.5 mH inductance delivering power of 10 kW at 500 Hz and 700 Hz is also used in this study.

The simulated results [10], for the case under study at 500 Hz using the analysis in section IV, shows that there is an E_a value for which V_{ac} is minimum. For this value of E_a for which minimum Vac is achieved, the per unit kVA rating, base equal to 10 kW peak, required to deliver constant power of 1pu is less than 2*pu* for a very wide range of phase angle (Less than 30° leading to 90° lagging). At unity power factor for the generator, a converter kVA requirement of values less than 1.414 per unit is required. Also, the kVA rating of the generator, and the converter are found to be equal at generator phase angle of 30° lagging.

Table I shows the results of the suggested method in this paper for the case under study.

TABLE I
SIMULATED RESULTS OF THE SUGGESTED METHOD FOR THE CASE UNDER STUDY

CASE	500 Hz	700 Hz
E_a (V)	712.54	748.88
V_{ac} (V)	712.54	748.88
I_a (A)	15.53	17.27
S_G (kVA)	11.07	12.93
S_C (kVA)	11.07	12.93
PF (%)	90.37	77.31

From the results above it can be seen that, while delivering constant power, the converter rating can be controlled by varying the back emf and the phase angle. The best operating point occurs at the point for which the trade off between the converter kVA and the generator kVA is desirable.

Also, it is shown that the magnitude of the controlled voltage for a given output power depend on the speed of the generator and the power factor level.

VIII. CONCLUSIONS

A proposed method is presented for finding the optimum trade-off point using Simplex method. It has been shown that for a given power factor and speed there is an optimum operating condition for which minimum kVA requirement for both the converter and the generator can be achieved. The trade off between the converter kVA rating and the generator kVA rating is a function of the power factor level at which the generator is expected to operate.

The kVA rating of the generator and the converter must be equal at a specific phase angle. There is a trade off between the kVA rating of the generator and that of the converter. This trade off is dependent on the power factor at which the generator is operating. This generator configuration can be controlled to achieve an optimum trade-off of converter and generator depending on requirements.

Two cases are tested, and the general performance of the proposed method is satisfactory, providing improvement of power factor correction, compared with other published results.

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BIOGRAPHY

Ahmed Faheem Zobaa (M'01-SM'04} received the B.Sc.(hons.), M.Sc. and Ph.D. degrees in Electrical Power & Machines from the Faculty of Engineering at Cairo University, Giza, Egypt, in 1992, 1997 and 2002.

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