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A New Test Set to Synchronous Generator Sudden Three-phase Short-circuit Based on Power Electronic Technique and Micro-controller Technique

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ABSTRACT

In order to avoid the influence of second-order component and other high-order components caused by three phases not shorted simultaneously in short-circuited currents on the generator parameters, the fast turn-on feature of power electronics elements (microsecond level) is applied. This paper analyzes in principle and designs a close set applied to synchronous generator sudden three-phase short-circuit test based on power electronic technique and micro-controller technique. It can realize the mentioned idea and can control the point at which the short is imposed, such as the point of one phase voltage crossing zero. The paper states the realizing principle of this kind of short set, analyses that electronic switches give rise to voltage distortion factor using discrete Fourier series, and discusses the influence of GTO turn-on resistance on the test precision, lastly validates its feasibility through simulation which model is configured with the design parameters of a turbo-generator (QFSN-650-2) to identify the transient quantities by nonlinear least square method, where the voltage-distortion factor is less than 0.202×10^{-3}, which meets the requirement of the test standard.

KEYWORDS-synchronous generator, sudden three-phase short-circuit test, close set, distortion factor

1. INTRODUCTION

Besides the generator's dynamic parameters can be determined by high-precision numerical recipes [1, 2], it is also necessary to improve test means and test automation to enhance quantity-estimated accuracy. One of the main factors influencing on the test precision is the demand that the three-phase need to be short-circuited practically simultaneously. According to the British standard [3] and IEEE standard [4], the phase contacts should close within 15 electrical degrees of each other. The contact's mechanical time constant is much larger than the period of voltages, so it is very difficult to control the point in the cycle at which the contract is closed. This will result errors from neglecting second order component and other harmonic components in short-circuit current, furthermore, the failure that the contactors fail to be closed on the three phases simultaneously causes harmonic components increase. Seriously, the test must be done again. This is a risk on the safety of the machine.

Based on the problems, Using modern power electronic technique and micro-control technique[5, 6], this paper designs a novel close set model applied to sudden three-phase short-circuit test. Generally, the GTO time (T_{on}) from off state to on state is very short (microseconds), so using GTO as the switching elements can impose three phases short at the same time and at arbitrary point of one phase voltage. For example, at the point that one phase voltage crossing zero (such as $u_a =0$), there will be no non-period component and second order component currents in the short current i_a. Thus, this equipment can control contents of DC component and second current component caused by DC component and avoid harmonic currents arising from that three phases are not shorted simultaneously.

2. Close-set topology and control strategy

2.1 Close-set topology

In view of operating safeties, the device is designed to insulated structure shown in Fig. 1., where S_1 is an insulated switch, and switching elements are GTO. Also R_a, X_a, R_b, X_b, R_c, X_c represent three-phase resistances and synchronous reactances respectively. In Fig. 1, the six switching elements are regarded as one group.

$N_p=I_{lm}/I_{max}$, where N_p is the necessary parallel groups, I_{lm} is the possible largest short current; I_{max} is the permitted maximum amplitude of current through one GTO.

2.2 Control of Time sequences applied to sudden three-phase short circuit test

Insulated switching S_1 keeps open until the test begins to protect the switching elements and operators. Fig. 2 shows time sequences to control the set components respectively. The time sequences are presented.

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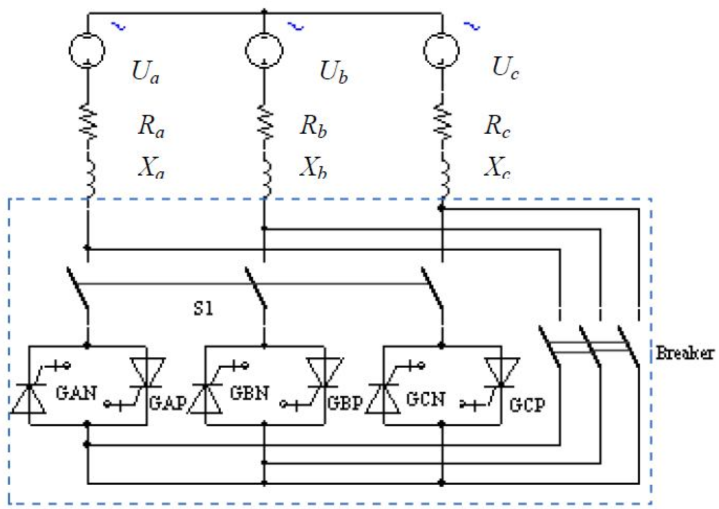

Fig.1 Topology of the close set

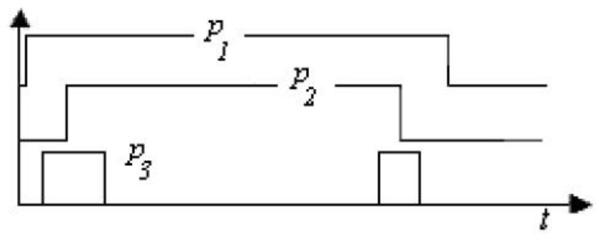

Fig. 2 Set control of Time sequences

(1) The control signal P_1 keeps high from the beginning to the end of the test, i.e. S_1 is closed during the test.
(2) In terms of the test demands, such as at the point one phase voltage crossing zero or reaching maximum value. All GTO elements will be triggered on or off, shown as pulses P_3 in Fig. 2. A GTO will turn on or turn off periodically determined by the voltage.
(3) The contactors controlled by P_2 in Fig. 2 are not turned on until the short circuit of all three phases is established by GTO elements or are on state before the largest value of current happened passing half time of one period of the voltage from the shorted time.
(4) After all contactors being switched on, all switching elements are turned off.
During ending the test, the control sequences are followed as:

(1) Giving triggering signals to all GTO is ready to turn the contactors off.
(2) Setting P_2 off state to switch the contactors off.
(3) After all contactors being broken in the circuit, all switching elements are turned off.
(4) In the end, setting P_1 zero to turn S_1 off.

There are also some advantages in the set. One advantage is that every two GTOs connected in reverse parallel way continuously permit current flow each other. A second and more useful advantage is that the contactors turn on or turn off without arc because the GTO's on state voltage (U_{on}) less than 10 volts (in Fig. 1).

2.3 Analysis of the voltage distortion factor caused by GTO [7, 8]

A-phase voltage discrete function can be expressed as follows:

$$u_a = U_m \sin \omega_1 t$$

$$F(n\omega_1) = \frac{1}{t}\int_{-\frac{T}{2}}^{\frac{T}{2}} u_a e^{-jn\omega_1 t} dt, \quad u_a = \sum_{n=-\infty}^{\infty} F(n\omega_1) e^{jn\omega_1 t} \tag{1}$$

$$\omega_1 = \frac{2\pi}{T_1}, \qquad t = kT_s \tag{2}$$

Where

$U_m = \sqrt{2}U$, U is the root mean square of voltage,

ω_1 is synchronous rotational angular frequency,

$T_1 = NT_s$ is the continuous period of u_a,

T_s is sampling period,

N is the sample times one period T_1,

Only when T_1/T_s is a rational number, is the discrete function u_a periodic function. The distortion of voltages caused by the threshold voltage (V_{Th}) of GTO, expressed as

$$u_a = \begin{cases} 0 & k \langle k_0, \quad k \rangle \frac{N}{2} - k_0 \\ U_m \sin \omega_1 t & k_0 \le k \le \frac{N}{2} - k_0 \end{cases} \tag{3}$$

where k0 is sampling times when $u_a > V_{Th}$. Rewriting (3) as Fourier form

$$u_n = \frac{2}{N} \sum_{k=1}^{N} u_a(k) e^{-j \frac{2\pi}{N} kn} \tag{4}$$

where n=0,1,2,…, is harmonic order.

According to the characteristics of Fourier series, (4) can be expressed as

$$u_a(k) = U_m \left[\left(1 + \frac{2}{\pi} \sin 2\varphi - \frac{4\varphi}{\pi} \right) \sin \frac{2\pi k}{N} + 4 \sum_{n=3,5\Lambda} \left(\frac{1}{(n+1)\pi} \sin(n+1)\varphi - \frac{1}{(n-1)} \sin(n-1)\varphi \right) \sin \frac{2\pi nk}{N} \right] \tag{5}$$

$$\varphi = \omega_1 k_0$$

Transferring the harmonic components of voltage gained from (5) into the equation of the distortion factor of generator's voltage (6), F_{Di} can be calculated as.

$$F_{Di} = \frac{\sqrt{\sum U_n^2}}{U_{rms}} \tag{6}$$

where $\sum U_n^2$ is the sum of the square of all components of the voltage except the fundamental, U_{rms} is the root-mean-square value of the voltage. Generally, V_{Th}/U_m <0.01, i.e., φ<0.01 approximately, we have F_{Di}<0.0202%. So using GTO to control the breaker does not influence on the precision of the test.

3. Precision influenced by on-state resistance of gto (r_{on})

Because the value of R_{on} is almost the same as the generator's armature resistance R_a , the influence of the R_{on} must be analyzed on the precision of the parameters determined by the test.

First, the subtransient reactance x_d'' and transient reactance x_d' far exceed R_a, that is R_a is negligible, so the short currents mainly determined by x_d'' and x_d' , as shown in equation (7). R_a only influences the armature time constant T_a (Eq.8) deciding the speed of the aperiodic and double frequency components of short currents decaying as exponential function. One short current such as i_a, does not contain the aperiodic and double frequency components by controlling γ_0 =90 degrees. Therefore, the effect of R_{on} on the parameters determined by i_a can be neglected.

$$\begin{aligned} i_a &= \left[\left(\frac{1}{x_d''} - \frac{1}{x_d'} \right) e^{-\frac{t}{T_d''}} + \left(\frac{1}{x_d'} - \frac{1}{x_d} \right) e^{-\frac{t}{T_d'}} + \frac{1}{x_d} \right] U_m \cos(\omega t + \gamma_0) \\ &- \frac{U_m}{2} e^{-\frac{t}{T_a}} \left[\left(\frac{1}{x_d''} - \frac{1}{x_q'} \right) \cos \gamma_0 + \left(\frac{1}{x_d''} - \frac{1}{x_q''} \right) \cos(2\omega t + \gamma_0) \right] \end{aligned} \tag{7}$$

$$T_a = \frac{x_2}{R_a} \tag{8}$$

where T_d'' , T_d' are d-axis subtransient short-circuit time constant and d-axis transient short-circuit time constant respectively, γ_0 is the point in the cycle where the short is imposed.

(2) Then, based on the characteristics of the curve fitting and the short current reaching its peak after half time of T_0 from the point at which the short imposed, if the contactors are turned on before the short current reaching the peak, R_{on} does not affect fitting the envelope of i_a and has a negligible effect on the determination of aperiodic parameters.
(3) Finally, according to the features of GTO operating current and peak current, generally controlling the test needs several groups of GTO connected in parallel way. Thus, the groups' equivalent resistance scales down. To sum up, taking the above measures can reduce the effect of Ron on the precision.

4. CONTROL REALIZATION AND RESULTS

The main circuit and the controlling time sequences are shown in Fig. 1 and Fig. 2 respectively. The parameters of simulation model refer QFSN-650-2 turbo-generator design values. Three phases are shorted with the condition u_a crossing zero, that is u_a =0. The data are sampled by simulating and are dealt with MATLAB as shown in Fig. 3, where i_B, i_{GTO}, i_a are the current curves through the contactor, GTO and A phase respectively, u_a is the wave of A phase voltage. Applying the switching characteristic of power electronic elements GTO can ideally realize three phases that are shorted concurrently. So the hi-tech application also helps to the identification of generator dynamic parameters.

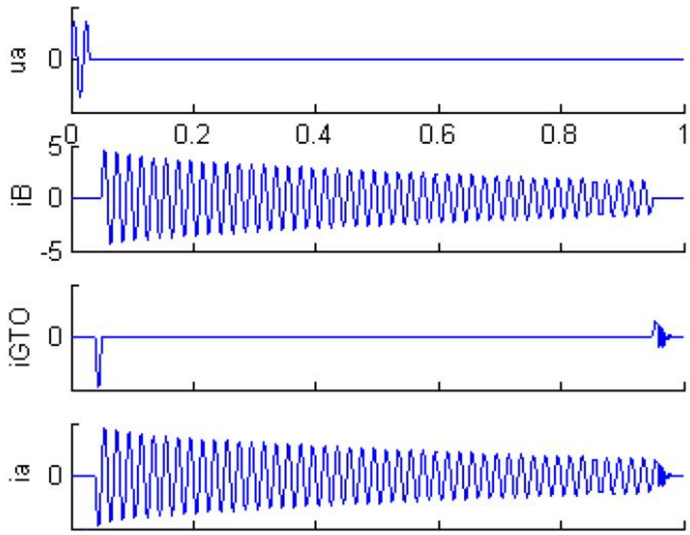

Fig. 3 Waves of currents and voltage

The parameters identification by the method of nonlinear least square is shown in Table 1. Because of not containing aperiodic and double frequency components in short currents i_a, the results is closer to the design data than the data identified through the test with breakers.

Table 1 Data comparison of different methods with design data

	x_d	x'_d	x''_d	T_d	T''_d	T'_d
Design	0.2155	0.3258	0.2414	0.261	0.035	1.016
Identification	0.2158	0.3249	0.2367	0.262	0.035	1.014

5. Conclusion

The research on the principle of shorting circuits by means of electronic switches and the system simulation indicate that the close set integrated power electronics and its control technique can automate short-circuit operation of the sudden three-phase short-circuit test of synchronous generator to enhance controlling precision of short-circuit test. That is applying the fast turn-on character of power electronic components to realize three phases shorted simultaneously and one phase short circuit imposed at any point in the cycle. Even though using ultra high-speed switch [9], it does not conduct at any point where the short is imposed. If this set is used, it can avoid the effects of the shaking contactors during shorting circuit on the test data too and because of the voltage between the contactor's terminals is less than 10 volts, the contactors turn on or off without arc. This close set can also be used other tests such as armature voltages recovery test.

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