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A brief review of super-excitation schemes in short-circuit generators

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Most short circuit generators have static excitation systems to supply field current to the rotor circuit. All synchronous alternators suffer a reduction in the terminal voltage due to high armature reaction which is a result of the extremely high magnitude short-circuit currents. The reduction in terminal voltage will lead to a corresponding reduction in the stator current magnitude. The short-circuit generators are expected to maintain a constant magnitude of current for specified duration to complete the tests as per corresponding standards. Hence the short-circuit generators invariably make use of super-excitation to maintain the required magnitude of short-circuit currents for specified duration. During circuit breaker testing, it is required to maintain the recovery voltage at pre-fault levels. This requires significant over excitation of the machine. This paper presents a brief review of the methodology and algorithm of super-excitation schemesadopted in short circuit testing along with actual data recorded at the High Power Laboratory at CPRI, Bangalore.

Keywords: *Short-circuit generators, transient behavior, super-excitation.*

1.0 INTRODUCTION

The short-circuit characteristic of synchronous generators has been the subject of great scrutiny and research over the years. The short-circuit transient currents can reach high magnitudes due to the transients associated with damper winding and field winding in the sub-transient and transient periods respectively [1]. In short circuit generators, it is required to maintain the short – circuit current magnitude for the required duration as per the relevant testing standards. This increase in excitation current is referred to as 'super-excitation' [2]. In this paper, the methodology of super-excitation is presented with special reference to the 2500 MVA, 14 kV, 3000 rpm, 50 Hz short-circuit generator at CPRI, Bangalore. The recorded data during some short-circuit tests performed on electrical equipment,is presented to illustrate the effect of super-excitation.

2.0 DEMAGNETISING EFFECT OF ARMATURE CURRENT

A concise review of the short-circuit phenomenon of short-circuit transients in synchronous machines is presented here. The equation for the terminal voltage of a short circuit generator is given below [3]:

$$V_a = -R_a I_a - jX_s I_a + E_{af} \quad ....(1)$$

Where E_{af} represents the induced emf before the synchronous reactance and I_a represents the stator current. X_s and R_a stands for synchronous reactance and armature resistance. The short-circuit generator will have low values of synchronous reactance and armature resistance compared to conventional generators. This causes an extremely small duration sub-transient state. The surge in current magnitude in the sub-

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transient period can be easily observed in the current waveforms. But soon there is a decrease in current magnitude. The effect of armature current is entirely demagnetizing as it is almost zero power factor lagging.It is desired to maintain the current regulation to meet the testing requirements for a few hundreds of milliseconds.

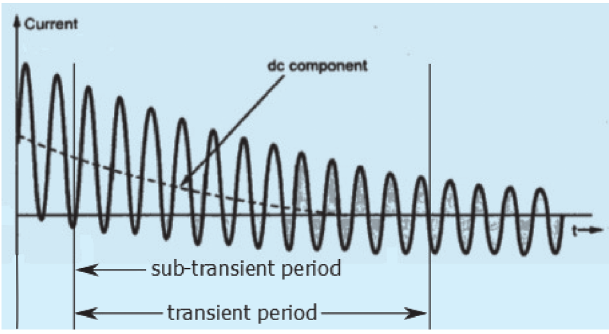

FIG. 1 SHORT CIRCUIT CURRENT WAVEFORMS IN A SYNCHRONOUS ALTERNATOR

After the short circuit, it may be required to maintain the recovery voltage equal to the applied voltage before the short circuit in case of circuit breaker testing [4]. Hence super-excitation is required to counter act the demagnetizing effect of armature reaction [2]. For illustration, the short circuit current waveforms of a synchronous alternator is presented in Figure 1.

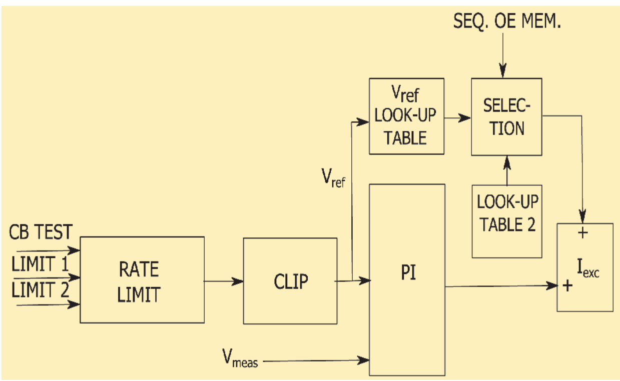

FIG. 2 FUNCTIONAL BLOCK DIAGRAM OF VOLTAGE REGULATOR MODE

3.0 EXCITATION SYSTEM

The short circuit generator at High Power Laboratory, CPRI uses the static excitation system. The excitation transformer feeds the Thyristor Bridge which rectifies the three phase alternating current into DC current. The DC current is fed to the rotor using carbon brushes and slip rings. During the generator mode, the firing angle is controlled in two different modes – current regulator mode and voltage regulator mode [5]. In motor mode, voltage regulator mode is always active. In generator mode, before the onset of the short circuit current, the terminal voltage of the generator is maintained by the excitation control system operating in the voltage regulator mode. The functional block diagram of the voltage regulator mode is presented in Figure 2.

The Rate Limit block sets the required rate of rise of the voltage reference signal. The permitted rate of rise is higher when circuit breaker testing is involved. The reference signal is clipped and then is sent to the PI regulator block. PI block also receives the measured voltage signal. The voltage reference signal also reaches the look-up table block 1. When the sequential over-excitation memorization signal goes high, then the over-excitation look-up table 1 is selected. On the other hand, when the signal is low, a constant over-excitation correction (Look-up table 2 in Figure 2) is applied.

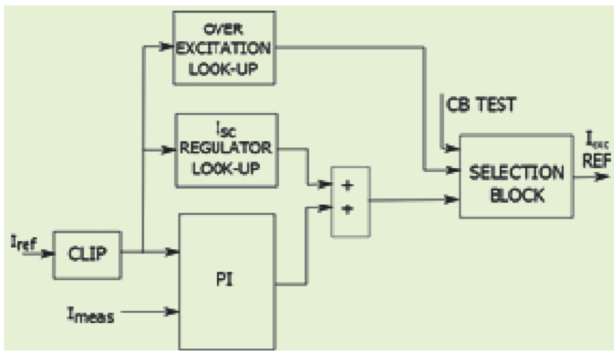

FIG. 3 FUNCTIONAL BLOCK DIAGRAM IN CURRENT REGULATOR MODE

The over-excitation signal is added to the PI regulator output. The voltage mode is active only when short circuit current is zero. Hence the real challenge in excitation comes in the current mode which is active during the short circuit. The mode of operation in the current mode also has two sub-modes of over-excitation. The over-excitation regulator sub-mode is active when the circuit breaker testing is carried out while the I_{sc}regulator sub-mode is active for every other test [4]. The functional block diagram is presented in Figure 3.

The reference short circuit current is first clipped by the clipper block and then is sent to the PI regulator block. The I_{sc} regulator block also receives the same signal and produces an output based on a look-up table pre-programmed during the commissioning of the system which is entirely based on the exact magnetization characteristics of the specific machine. During circuit breaker testing, the entire over-excitation sequence is based on a look-up table which is also based on the exact characteristics of the machine. But the excitation current reference would be much higher in the second case to ensure sufficient power frequency recovery voltage during the O-CO-CO testing sequence. The exact magnetization characteristics of the generator at HPL with different over-excitation levels is illustrated in the Figure 4 [6]. The drop in the short circuit current becomes lesser prominent with increase in the over-excitation factor.

The look-up tables serve to boost the excitation current referencein current regulation, voltage regulation and over excitation modes respectively. These look-up tables, based on the exact characteristics of the machine, are the real sources of super-excitation in the short circuit generator [5]. The sequential over-excitation memorization signal is a logic signal which triggers the output from the voltage regulation and I_{sc} regulator look-up tables.

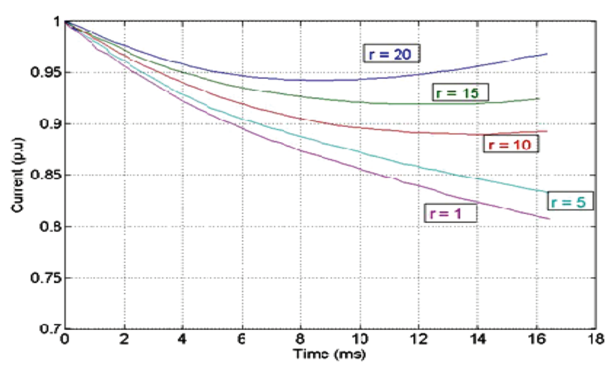

FIG. 4 VARIATION OF STATOR CURRENT EXCITATION FACTORS (R)

4.0 RECORDED WAVEFORMS

The voltage and current waveforms along with the control signals were recorded using PERTU software, during several tests conducted at High Power Laboratory.

The waveforms recorded during transformer testing with over-excitation is shown in Figure 5.

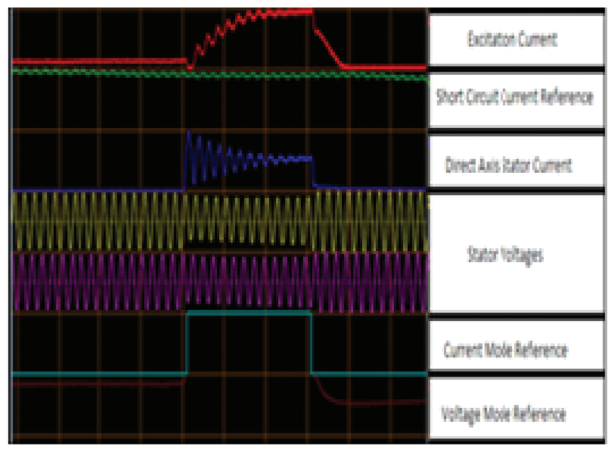

FIG. 5 STATOR CURRENT AND VOLTAGES DURING SHORT-CIRCUIT TESTING ON TRANSFORMERS

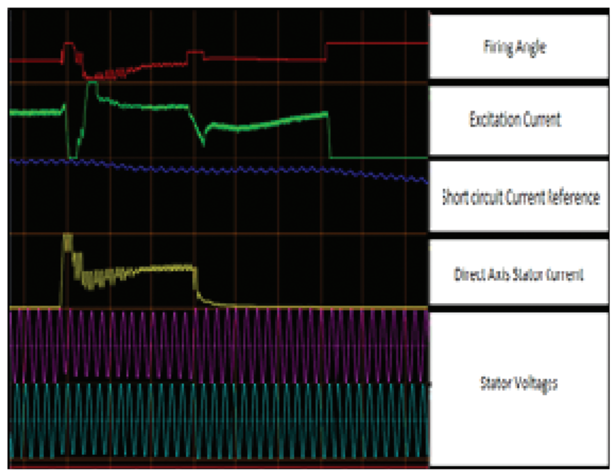

FIG. 6 STATOR CURRENT AND VOLTAGES DURING SHORT-CIRCUIT TESTING ON TRANSFORMERS – 2

The direct axis stator current is the parameter used for drive control and hence that is shown in the waveforms instead of the normal line currents. The increase in the magnitude of the short circuit current initially, due to the low sub-transient reactance, is clearly discernible from the waveforms. This also leads to a decrease in the excitation current temporarily. The voltage magnitude falls considerably during this period as can be seen from the waveforms. There is a drastic reduction in current magnitude subsequently, when the demagnetizing effect of stator current overtakes the sub transient phenomenon. The PI regulator would drive a huge increase in the excitation current as is clear from the waveform. For better illustration, a similar waveform is provided in Figure 6.

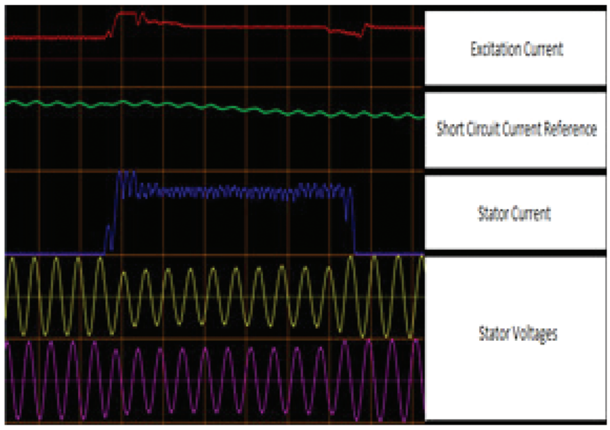

FIG. 7 STATOR VOLTAGES AND CURRENT DURING A POWER ARC TEST ON INSULATOR STRING

Figure 7 presents the waveforms during a power arc test on an insulator string which calls for very high current magnitude for a duration of 250 milliseconds. The immediate heavy decrease in the magnitude of the stator voltage compared to the pre-fault level is the most prominent feature. The immediate increase in the stator current and the subsequent fall in excitation is not conspicuous as in the earlier cases. The testing on circuit breaker is the most interesting and hence it is presented in greater detail. The over-excitation signal which drives the excitation purely from a look-up table will be highlighted in all the waveforms. The sequential over-excitation memorization signal, which was active previously during current mode, is now active during voltage mode also. The waveforms during a normal circuit breaker test are presented in Figure 8. For academic purpose, circuit breaker testing was carried out without the over-excitation signal and the waveforms are presented in Figure 9 for comparison. The current mode signal coming from PI controller and Isc regulator, which was zero in the earlier case, is now present, as is evident from the figure. The increase in excitation current is not as swift as in the previous case. Even the recovery voltage is sluggish without the over-excitation signal.

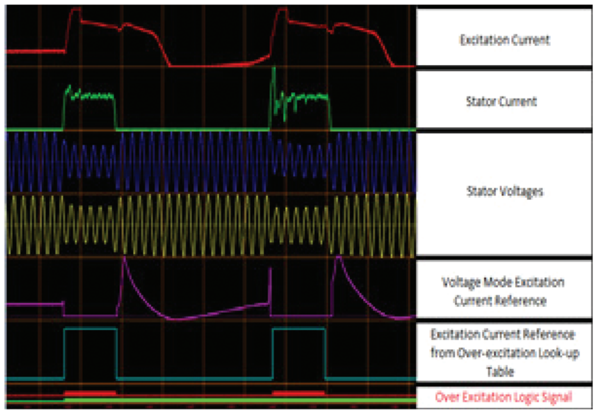

FIG. 8 MEASUREMENT DURING CIRCUIT BREAKER TESTING

The test sequence presented is O-CO operation by test breaker which is required as per standards[4], [7]. The red logic signal at the bottom is the over-excitation signal passed on to the excitation controller by the Synchronous Test Processor. The green logic signal indicated below is the Sequential Over-excitation memorization signal which enables the Short circuit current look-up table, which is rendered moot by the over-excitation signal.

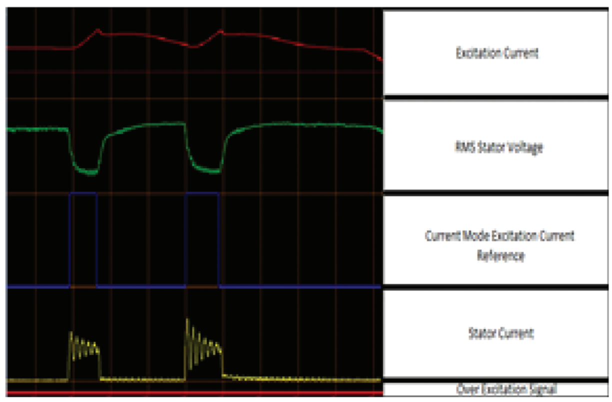

FIG. 9 MEASUREMENTS DURING CIRCUIT BREAKER TESTING WITHOUT OVER-EXCITATION

In order to illustrate the excitation reference after current interruption, Figure 10 is added. The RMS Stator Voltage dip is highlighted by adjusting the scales while the voltage mode PI regulator output is shown clearly. A constant depending on the actual magnitude of the stator current is added from the voltage mode over excitation look-up table to form the total voltage mode excitation current reference. It can also be noted that the voltage mode output is zero during the actual short circuit.

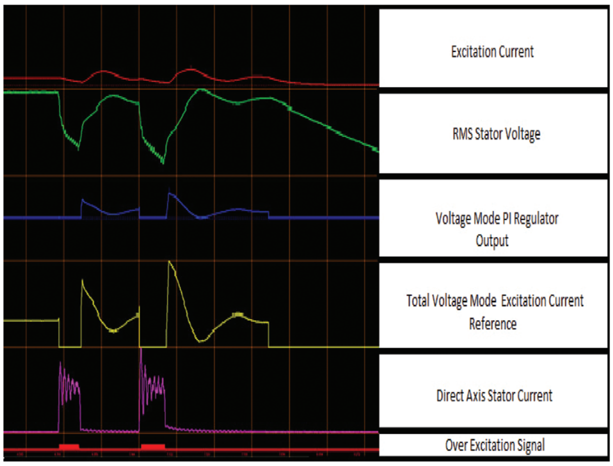

FIG. 10 VOLTAGE MODE SIGNALS DURING CIRCUIT BREAKER TESTING

5.0 CONCLUSION

The principle of excitation control in short circuit generators is presented in this paper, throwing light on super-excitation. The necessity to maintain the terminal voltage and the short circuit current magnitude to meet test requirements is the main driving force in designing the regulation principle.

The voltage mode and current mode regulation block diagrams are presented outlining the salient functional blocks. Super-excitation used to counteract the demagnetization effect of the short circuit currents is highlighted. Recorded waveforms have been included illustrating each of the explained cases. Special emphasis has been provided to present the case of circuit breaker testing where the over excitation function is used to maintain required power frequency voltage after fault as well as short circuit current magnitude during fault.

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