Effect of Three-Phase Fault in the Single-phase to Three-phase Solid State Transformer using MATLAB Simulink

Manali Sharma, Monika Jain, C.S. Sharma, Deepti Jain
Department Electrical Engineering Samrat Ashok Technological Institute

***Abstract*— In the proposed work, MATLAB Simulation of 1-phase to 3-phase Power electronic transformer (Solid state Transformer) is presented using MATLAB Simulink. The principal of operation of SST is described in detail. Firstly, the general performance of 1-phase to 3-phase Solid State transformer is presented using Resistive load and RL Load. The effect of Three-phase dead short circuit fault at the output terminal of SST will then be analyzed using MATLAB Simulink. Focus is given on the effect of input and output current due to short circuit fault at the output terminal of SST under different load condition is presented.**

***Keywords*— SST, Solid-State Transformer, IGBT, Inverter, SPWM**

I. INTRODUCTION

The conventional oil immersed transformer is the cheap and efficient method for voltage level transformation and isolation. Still this transformation using magnetic medium introduces unwanted characteristics into the modern power grid and also some other drawback are also there among which are the following:

1) The output voltage is a direct representation of the input voltage. Any noise or harmonic arises from the input, such as voltage sag, voltage swell or frequency variations will be reflected at the output.
2) The output current will also get reflected same as the input current.
3) Also at the output of transformers, Single phase residential customers introduces odd harmonics especially the 3rd, 5th and 7th with values in excess of 15 % of the fundamental. As with the total 3-phase load, the harmonics are rarely balanced among the three phases. With delta connected primary transformers the 3rd harmonic circulates in the primary winding and does not propagate to the network, but it cause unobjectionable primary winding losses.
4) The conventional oil immersed transformer will occupy more space and bulky due to heavy size and weight of core. The Solid-State Transformer is an emerging technique of power transfer by stepping up or stepping down the voltage and current in the compact module. However it is not used commercially as of now, But continues research and development on the concerned technique will definitely bring the work up to the commercial prospects.

The Solid-State transformer is AC (at 50 Hz) to AC (at 50 Hz) converter, the output and input of which operates at power frequency i.e. 50 Hz like the conventional transformer but at the inner circuitry, the operating frequency will be as high as in the range of several KHz (5 KHz is operating frequency in the proposed work), unlike in the conventional transformer.

II. PRINCIPAL OF SOLID STATE TRANSFORMER

For conventional oil immersed transformer, the operating frequency is 50 Hz due to which the required flux for inducing the required voltage is directly proportional to ratio of Voltage and frequency. The important requirement of transformer is that the cross-sectional area of core should be sufficient so that the required flux can be setup for inducing the required voltage at the secondary and primary winding. For solid state transformer, operating frequency is in terms of KHz and due to which the required flux for inducing the required voltage in the secondary winding (=V/f) is very less and hence the required cross-sectional area of core is also very less as compared to conventional oil immersed transformer. Due to which, the space requirement for this type of transformer is very less and can be made compact. The power frequency ac supply will be first converted into dc by diode bridge rectifier. then the high voltage dc supply will be converted to low voltage dc supply by Dual active bridge converter as shown in fig.1. Low voltage dc supply then converted into sinusoidal ac low voltage supply by SPWM power frequency inverter.

III. MATLAB SIMULATION OF SINGLE-PHASE TO THREE-PHASE SOLID STATE TRANSFORMER

Before analyzing the fault on solid state transformer, simulation of solid state transformer under normal load condition is necessary. In this section, the modeling of 63 KWatts, $11/\sqrt{3}$/0.415 KVolts, 1-phase to 3-phase, 50 Hz, Solid state transformer is done using the MATLAB simulink. The simulation diagram of proposed solid-state transformer is shown in fig. 1.

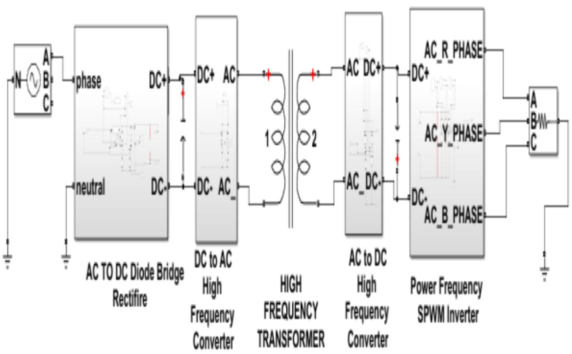

Fig. 1. Simulation diagram of 63 KVA 1-ph TO 3-ph Solid State Transformer having under normal load condition

Starting from the left side, the supply source is $11/\sqrt{3}$ KV, 1-phase, 50 Hz. At the first stage of conversion, the power frequency ac is converter into dc. The High voltage dc is then converted into high frequency ac for feeding the same to High frequency transformer.

The high frequency, high voltage ac is step down to a low voltage ac. The high frequency low voltage ac then again converted into low voltage dc. The low voltage dc is then converted into power frequency i.e. 50 Hz Sine wave which can be utilized same as that of conventional transformer. In the proposed strategy, control of ac output voltage will be through the power frequency SPWM inverter. The sequence wise operation of solid state transformer can be understood by the following block diagram as shown below :

1-Phase, $11/\sqrt{3}$, 50 Hz, AC source with series line current smoothning inductor

⇩

1-phase, Full bridge Diode Rectifire

⇩

High Voltage DC to High frequency High Voltage AC Converter

⇩

High Frequency Step down Transformer

⇩

High frequency AC to Low Voltage DC Converter

⇩

3-Phase SPWM based Power frequency Inverter

⇩

3-Phase Filter and Load

Fig. 2. Flow chart showing the sequence of power flow in the solid state transformer

In the proposed work, as shown in fig. 2, the output load voltage is controlled by varying the amplitude modulation index of SPWM inverter. One phase of 3-phase ac voltage source is used for simulation, the values of parameters of 3-phase ac source are mentioned in table I. The inductor at the input of diode bridge rectifier improve the quality of input line current.

The two converters on the either side of high frequency transformer having dc link capacitor on both side and high frequency transformer itself constitutes the Dual active bridge converter. The switching device used in both the converters is IGBT with feedback diode. As it is the dual active bridge converter, hence switching signals given to both the converters will be of same type. As the important feature of dual active bridge converter is that it operates at higher frequency to decrease the core size of high frequency transformer to make it more compact and less spacious.

TABLE I. PARAMETERS OF INPUT SUPPLY USED TO SIMULATE THE 63.0 KW SOLID STATE TRANSFORMER

S. no	Name of Parameters	Value of that parameter

1	Line to neutral Voltage	11000/√3Volts(L-N)
2	Inductor	500 mili-Henry / phase
3	Resistance of inductor	1mOhm
4	Input supply frequency	50 Hz
5	PIV of Diode in Diode bridge rectifier	11000/√3 Volts
6	Capacitance of DC link capacitor	10 µF

In the proposed method, the high frequency transformer has the operating frequency 5000 Hz. The parameters of concerned transformer selected is shown in table II.

TABLE II. PARAMETERS OF HIGH FREQUENCY TRANSFORER USED TO SIMULATE 63 KW SOLID STATE TRANSFORMER

S.no	Name of Parameters	Value of that parameter
1	Nominal Power and frequency	100 KVA and 5000 Hz
2	Primary Winding voltage, winding resistance and Inductance	8000 Volts, 0.1 Ohm and 8 micro Henery
3	Secondary Winding voltage, winding resistance and Inductance	3500 Volts, 0.00152 Ohm and 0.32 micro Henery
4	Magnetization resistance and inductance	8000 Ohms & 50 Henery

SPWM inverter is the stage of concerned transformer, where the rectified dc supply will be converted into 3-phase LV supply at line frequency i.e. 50 Hz. In the proposed work, the output voltage of Solid-state transformer will be controlled by the changing the value of Ma (amplitude modulation index) of SPWM inverter. The quality of output & input current is not seen effected by the change in amplitude modulation index of SPWM inverter for the given operating range of Ma. As shown in the table III, the range of values of amplitude modulation index lies in between 0.4 to 0.92. The result of simulation is checked by changing the value of amplitude modulation index ranging from 0.4 to 0.92.

TABLE III. PARAMETERS OF LINE FREQUENCY SPWM INVERTER SELECTED FOR SIMULATION

S. No.	Name of Parameters	Value of that parameter
1	Amplitude modulation index of SPWM inverter	0.4 < ma < 0.92
2	Frequency modulation index	mf=3800/50 = 76

The three-phase LV filter of low pass type rated 415 Volts, 50 Hz is designed to reduce the higher order harmonics from the output voltage and current of SPWM inverter. The selection of values of LV filter is very difficult for varying type of load, as the high value of inductor will cause the more voltage drop across the filter or high value of capacitor will cause the maximum current to go through the capacitor. The selection of filter parameter will be taken such that the output voltage will be almost the pure sinusoidal wave for changing load values.

For the varying value of load, the parameters of filter i.e. capacitor and inductor for simulating the Solid state transformer is mentioned in table IV.

TABLE IV. PARAMETERS OF LV FILTER OF SOLID- STATE TRANSFORMER

S. No.	Name of Parameters	Value of that parameter
1	Value of capacitor used in the filter	150 µF, 240 Volts
2	Value of inductor used in the filter	20 milli-henry, 100 Amps, 240 Volts

IV. SIMULATION RESULTS UNDER NORMAL WORKING CONDITION

Under normal condition, the simulation is done for rated load of 63 KW and unity power factor. Under this condition, the input current, output current and output voltage of SST is analyzed with their %THD.

Case-1: For load of 3-phase, 50 Hz and 63 KW, at unity power factor, the rms value of input and output voltage and current with amplitude modulation index of SPWM based line frequency inverter is tabulated in table V and mentioned below. The wave shape of input and output current of SST during the condition of unity power factor load is shown in fig. 3, the %THD of which observed as 38.1%.

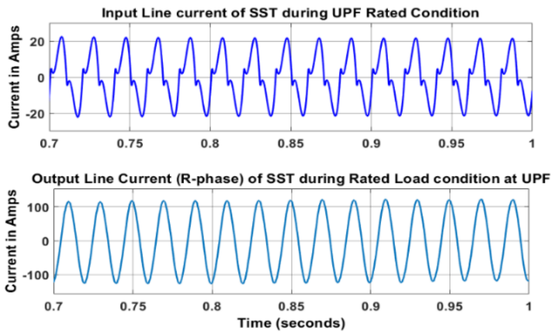

Fig. 3. The waveshape of input line current at 11 KV side and at the output side of solid state transformer for pure resistive load of 63 KW

TABLE V. SIMULATION RESULTS OF SST FEEDING THE LOAD OF 63 KW AT UNITY POWER FACTOR

S. No.	Name of parameter	Simulation Results for unity power factor load of 63 KW
1	Input Line current at 11 KV side and its %THD	14.18 Amps & 38.1%
2	Output Line current on LV side and its %THD	88.71 Amps and 1.9%
3	Output Line to Line Voltage rms value	413.2 Volts
5	Active power input to SST	70.4 KW
6	Reactive power input to SST	48.3 KVAr
7	Active Power Output of SST	64.3 KW
8	Reactive power Output to SST	0 KVAr
9	Amplitude Modulation index	0.62
10	Total Losses in SST	6.1 KW

Case-2: For 3-phase load of 63 KW at power factor of 0.8 lag, the rms value of input and output voltage and current with amplitude modulation index of power frequency inverter is tabulated below in table vi. The wave shape of input line current and output line current of concerned transformer during this condition is shown in fig. 4.

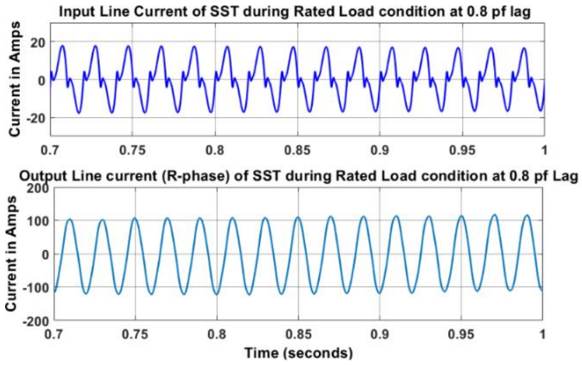

Fig. 4. The waveshape of input line current at 11 KV side and at the output side of the concerned transformer for 3-phase load of 63 KW at pf of 0.8 lag.

TABLE VI. SIMULATION RESULTS OF SST FEEDING THE LOAD OF 63 KW AT POWER FACTOR OF 0.8 LAG

S. No.	Name of parameter	Value of that parameters for 0.8 power factor load of 63 KW
1	Input Line current at 11 KV side and its %THD	13.42 Amps & 41.2 %
2	Output Line current on LV side and its %THD	106 Amps and 2.85%
3	Output Line to Line Voltage rms value	400 Volts
5	Active power input to SST	66.81 KW
6	Reactive power input to SST	45.97 KVAr
7	Active Power Output of SST	59 KW
8	Reactive power Output to SST	44.4 KVAr
9	Amplitude Modulation index	0.84
10	Total Losses in the SST	7.81KW

V. SIMULATION RESULTS UNDER 3-PHASE FAULT CONDITION

As for the transformer, the most sever type of test is the short circuit test as per IS and IEC standards. In this test, for conventional oil immersed transformer, one of the windings of transformer is subjected to rated voltage and other winding is subjected to its three phase terminals short circuited. The purpose of this test is to check whether the transformer is capable of carrying the short circuit current for particular time. Along with that, for solid state transformer, it is also necessary to check by short circuit test, for how much time it can withstand the short circuit current without being unstable. In this section, the solid-state transformer is subjected to 3-phase dead short circuit fault at the output terminals of solid-state transformers as shown in fig. 5. For the short circuit studies in this section, load considered is pure resistive load of 63.0 KW.

Case 1 (Fault Clearing time is 0.08 sec & load Connected at output of SST is 63 KW): Here the three-phase fault was created at the time instant of t=0.48 sec, when the SST was feeding the rated load i.e. 63 KW at unity power factor. Due to three-phase fault, the output line current of SST is shown in fig. 5. The input supply line current feeding the SST along with its output is also shown in fig. 6. The load current is shown in fig. 7.

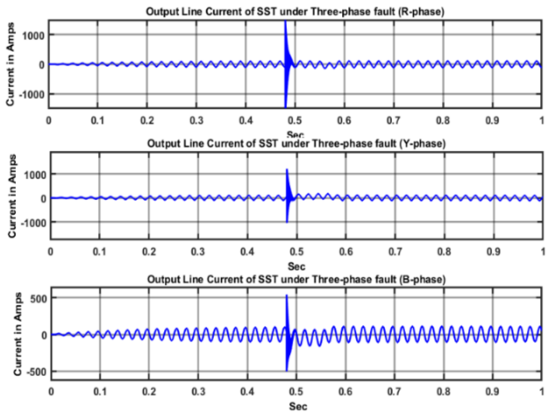

Fig. 5. Output line current of solid state transformer due to 3-phase fault at the output terminal of solid state transformer when the fault clearing time is 0.08 sec.

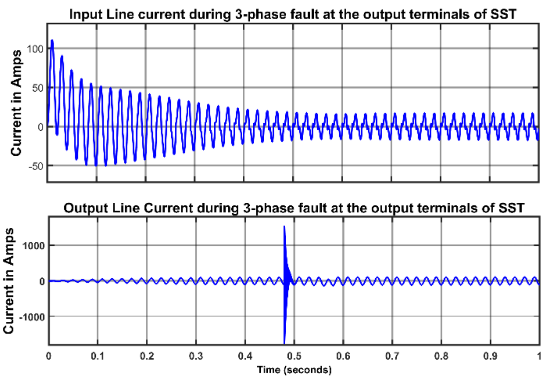

Fig. 6. Input and output line current of solid state transformer due to 3-phase fault at the output terminal of solid state transformer when the fault clearing time is 0.08 sec.

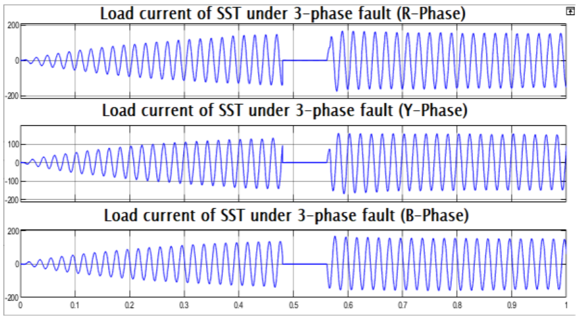

Fig. 7. Load current of solid state transformer due to 3-phase fault at the output terminal of transformer when the fault clearing time is 0.08 sec

Here in this case, the fault created or simulated in such a way that fault is cleared at time t=0.56 sec and it was observed that after the time instant when fault was cleared, system was restored to the pre-fault condition. In this case, the fault clearing time maintained is 0.08 sec.

It is interesting to observe the fig. 6, where there is no change in the input current, even there is three-phase fault on the output side of solid-state transformer unlikely in the conventional oil immersed transformer. This is the important feature of solid-state transformer.

Case 2 (Fault Clearing time is 0.16 sec & load connected at the output of SST is reduced to 30 KW at UPF): In this case, the simulation of 3-phase fault is done in such a way that the fault clearing time is increased from 0.08 sec to 0.16 sec & load is reduced to 30 KW, the wave shape of SST output line current, input line current with output current of SST and load current is shown in fig. 8, fig. 9 and fig. 10 respectively.

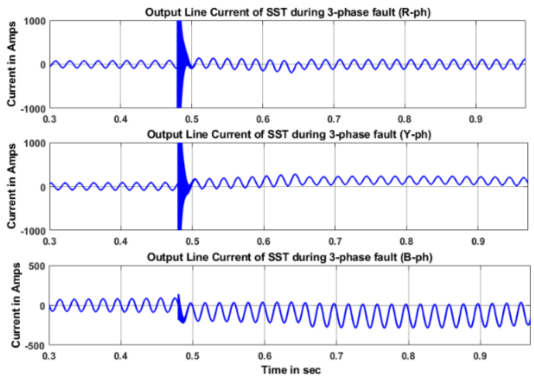

Fig. 8. Output line current of solid state transformer due to 3-phase fault at the output terminal of solid state transformer when the fault clearing time is 0.16 sec.

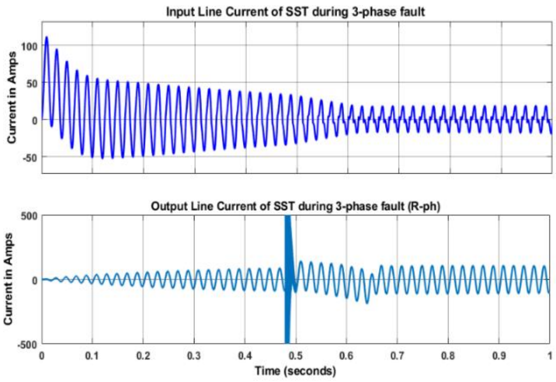

Fig. 9. Input and output line current of solid state transformer due to 3-phase fault at the output terminal of transformer when the fault clearing time is 0.16 sec.

It is observed that on increasing the fault clearing time from 0.08 to 0.16 sec, the system is not able to restore its pre-fault condition. As it is evident from fig. 10 that the magnitude of current of Y and B-phase is different than the magnitude of current in R-phase.

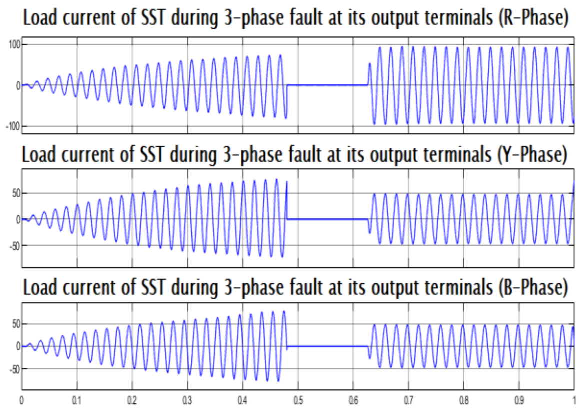

Fig. 10. Load current of solid state transformer due to 3-phase fault at the output terminal of solid state transformer when the fault clearing time is 0.16 sec

It is observed that with increasing the fault clearing time from 0.08 sec to 0.16 sec and decreasing the load to 30 KW, the system is not able to achieve the pre fault condition.

VI. CONCLUSION

As for as the normal operating condition of SST is concerned, it is observed that the solid-state transformer act as the source of reactive power, because if the load connected at the output of SST is RL Load, then it can be seen from table vi that the reactive power input to SST and reactive power output of SST is almost same, that means no extra magnetizing current is required by the solid state transformer, if the load is of lagging nature. Input line current taken by SST is less at lagging power factor as compared to when the load is unity power factor for the same value of active power output. Bidirectional power flow in the proposed strategy is not possible. However, the DC bus of two voltage levels is available in the SST. No tap changer is required to control the output voltage unlike in the conventional transformer. The voltage can be controlled by the amplitude modulation index of SPWM inverter. The proposed work also revels that fault clearing angle along with the fraction of load at the output also play a major role, while testing the solid-state transformer. If the fault clearing time is more than the specified limit then pre-fault condition is difficult to achieve.

Moreover, the input line current is not affected by the fault at the output terminals.

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