Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 6 (9): 1993-1999, 2006
ISSN 1812-5654

A Simulation Model of Solid-state Transfer Switch for Protection in Distribution Systems

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Abstract: This study deals with the application of a Solid-state Transfer Switch (SSTS) for protection in the distribution system that has been evaluated through modeling and simulation. The modeling of this SSTS is based on graphic models using the electromagnetic transient simulation program PSCAD/EMTDC. The SSTS for protection in distribution systems has been modeled with the objective of achieving faster interruptions. In the SSTS model, a new control scheme based on Park's transformation theory and three-phase proportional integral controlled phase locked loop has been proposed. Extensive simulations were carried out to validate the performance of the SSTS to transfer power to the load from a faulted feeder to a healthy one in a short period of time. Simulation results obtained also prove that the SSTS can mitigate voltage sag and protect bus bar voltage from various types of faults. It is observed that the impact of the induction motor load on the performance of the SSTS in which it has a higher time delay to complete the transfer process as compared to the system with static loads. The effectiveness of SSTS was also evaluated under various faults and load conditions and compared with the IEEE benchmark system STS-1 in terms of transfer time.

Key words: Solid-atate transfer switch, transfer time, control system

INTRODUCTION

Traditional switching practices such as mechanical switches have been applied for years in most utilities as an effective counter measure against long interruptions. These mechanical switches commonly take from 6 to 36 cycles to make a feeder transfer and recognition after a permanent fault has been detected (Sannino, 2001a; De Mello, 2005). However, the recent technological advancement in power electronics and power semi-conductor devices (e.g., thyristor) has allowed sharp reduction of times and transfer the system within 1/4th of a cycle i.e., around 5 ms with minimum transient (Palav and Gole, 1998). A solid-state transfer switch is used to protect sensitive loads from system side faults by transferring the load on to a healthy backup feeder swiftly, if there are any problems on the main feeder. The effects of system side faults result in outages, voltage swells and most predominant are the voltage sags. The SSTS is designed using thyristors only because of the high current capacity since the switch requires a continuous current rating equal to the load side faults level. Thyristor has a short time rating of 16 kA for 15 cycles, which is adequate for most 15 kV class applications. It also has low conduction loss compared to Gate Turn Off (GTO) Thyristor and insulated gate bipolar transistor (IGBT) (Woodley *et al*., 1994).

Thyristor based SSTSs have been long used in the medium voltage applications to replace electromechanical transfer switch for switching sensitive load between two distribution feeders. These are due to the availability of reliable semiconductor switches; stringent voltage quality requirements of sensitive load and slow operation of the electromechanical transfer switches (Hossein *et al*., 2000; Cheng and Chen, 2004). The transfer time is the utmost importance in the evaluation of a SSTS performance, since it reflects the duration of power discontinuity or interruption for the sensitive load. The power discontinuity, as a result of load transfer process by mean of a SSTS, is determined by the total transfer time. The total load transfer time is the sum of fault detection time and fault transfer time (Hossein *et al*., 2002). A fast solid state transfer switch employs a voltage detection logic based on transforming ac voltages into a synchronously rotating frame and a selective gating strategy based on the direction of current flow (Martinez, 2000).

The SSTS control considers both fault detection and transfer process. The SSTS fault detection is based on Parks transformation theory (Sannino, 2001b) in which it is described in terms of a block diagram as shown in Fig. 1. The instantaneous three phase voltages $V_a(t)$, $V_b(t)$, $V_c(t)$ are transformed into a two-axis coordinate system, known as the $\alpha\beta$-cordinate system using the following equation,

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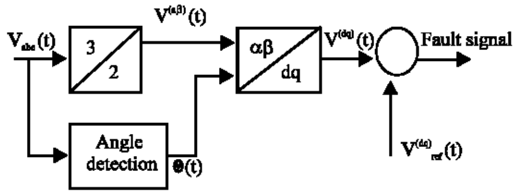

Fig. 1: Block diagram of the SSTS fault detection technique

$$\begin{bmatrix} V_\alpha(t) \\ V_\beta(t) \\ V_{(0)}(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} \quad (1)$$

where, V_0 (t) is the zero sequence voltage component.

The voltage vector is further transformed into a rotating dq-coordinate system using the equation,

$$V^{(dq)}(t) = e^{-j\theta(t)} V^{(\alpha\beta)}(t) \quad (2)$$

where, θ (t) is the transformation angle calculated as,

$$\theta(t) = \theta(0) + \int_0^t \omega(t)dt \quad (3)$$

Finally, the amplitude of the supply voltage vector is determined using equation,

$$V_{dq}(t) = \sqrt{v_d^2(t) + v_q^2(t)} \quad (4)$$

The amplitude of the supply voltage is compared to the threshold voltage, $V^{(dq)}_{ref}(t)$ in compliance to load sensitivity so as to detect the fault signal. However, the fault detection time is dependent on the nature of faults and the various types of voltage sag phenomena.

The SSTS control system considers a switching algorithm to transfer loads from the main feeder to the back-up feeder when an upstream fault occurs. There are two ways of transferring loads and they can be accomplished by using the make-before-break (MBB) and the break-before-make (BBM) transfer process. In the MBB transfer process, transfer operation can be accomplished rapidly by firing the thyristors in the static switch that is not conducting, that is, the one mounted in the backup feeder, before the current on the corresponding switch in the main feeder reduces to zero. As the current starts to flow in the thyristor that has just been fired, the conducting thyristor in turn is forced to turn off very quickly. Alternatively, in the BBM transfer process, the control system will not fire the thyristors in the backup feeder until the current through the thyristors in the faulted source switch has become zero.

In this study, we will describe and demonstrate the SSTS simulation model that has been developed to facilitate studies in power quality improvement. SSTS helps to protect sensitive loads from system side faults by transferring the load to a healthy backup feeder. This process involves several issues namely, the operation of device topologies and the design of control strategies, which are addressed in this study. In addition, we propose a new control scheme that can achieve better performance in the context of fast load transfer in terms of transfer time. SSTS performance is evaluated in terms of its load transfer times under various types of load and fault conditions.

SSTS MODEL AND ITS OPERATION

The basic model of the SSTS consists of two three phase solid-state static switches meant for the main and the back up feeders. These switches have an arrangement of each constituted in turn by anti-parallel thyristor per phase, which allow the fast transfer of power from a main feeder that is affected by a disturbance (voltage sag or short interruption) to a backup feeder (Alvarez and Alamar, 2000) with a sensitive load connected between the two feeders, as shown in Fig. 2.

This configuration of SSTS is almost similar to the single line diagram of IEEE Benchmark system SST-1 of (IEEE PES TF, 2001), but with different ratings.

Normally, in the operation of SSTS, the firing signal continuously energizes the thyristors of the main feeder while the thyristors of the back up feeder are being de-energized. When a three phase to ground fault occurs in the main feeder, the firing pulses of the main feeder stop, which in turn stop the conduction at first natural current zero and causing immediate turn off. At the same time, thyristors of the back up feeder become turn on and initiate load transfer from the main feeder to the back up feeder within a very short time. Once the fault of the system disappears, the main feeder switches are turn on whilst the back up feeder switches are turn off and the load is again transferred to the main feeder.

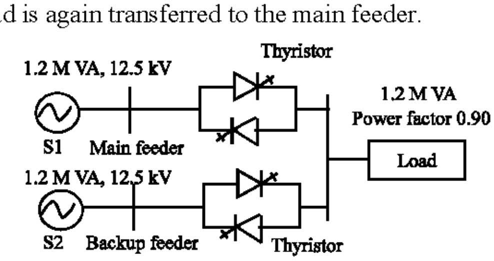

Fig. 2: Basic model of solid-state transfer switch

PROPOSED SSTS DESIGN

The proposed SSTS is designed using the components in PSCAD/EMTDC program (Olimpo and Acha, 2002).

Topology of the SSTS: There are two thyristors switches connected to two identical feeders having 1.2 MVA, 12.5 kV system voltage and a sensitive R-L load of 1.2 MVA, 12.5 kV and 0.90 power factor fed from two feeders as shown in Fig. 3. A three-phase to ground fault that originated from the main feeder is simulated. In the simulation, the resistive and inductive load parameters are determined by considering the load impedance, which is given by,

$$Z = \frac{V_L^2}{S_{3\phi}} \angle\theta = R + jX_L \tag{5}$$

where,

Z	:	Load impedance
θ	:	Power factor angle
R	:	Resistance of the load
X_L	:	Inductive reactance of the load
$S_{3\Phi}$	:	Three-phase load MVA
V_L	:	Line voltage at the load.

For V_L = 12.5 kV, load $S_{3\Phi}$ = 1.2 MVA, load power factor = 0.9 and power factor angle, θ = 25.84°. The resistance, R and inductance, L are calculated using Eq. 1 and found to be 117.18 Ohms and 0.18 H, respectively.

Under normal operating conditions, the control logic will only trigger the thyristor switches connected to the main feeder. When a fault occurs in the main feeder, the control logic will transfer the load to the backup feeder by removing gating signals from thyristors connected to the main feeder and triggering the thyristors connected to the backup feeder. When voltage is recovered, the load is transferred back to the main power source. Input signals to the control logic system are required for controlling the SSTS operation.

Control scheme of SSTS: The proposed control scheme for the SSTS operation is shown in Fig. 4 in which it can be divided into four parts namely, voltage detection transfer signal, current direction and zero crossing detection signal, synchronizing signal and firing control logic. The IEEE Benchmark SST-1 control system is based on Park's transformation. In this study, we proposed a new control system that considers both the Park's transformation and the three-phase PI controlled Phase Locked Loop (PLL). By using the PLL, we can obtain fast synchronization and accurate firing logic signals thus making the transfer response comparatively faster. This control scheme will be compared to the IEEE Benchmark SST-1 control scheme.

Voltage detection: For the voltage detection shown in Fig. 4a, the logic is based on the Park's transformation theory. The ac system's voltages are input into the PLL to produce synchronize signals, which in turn are fed into the abc to dq transformation block. Output of the

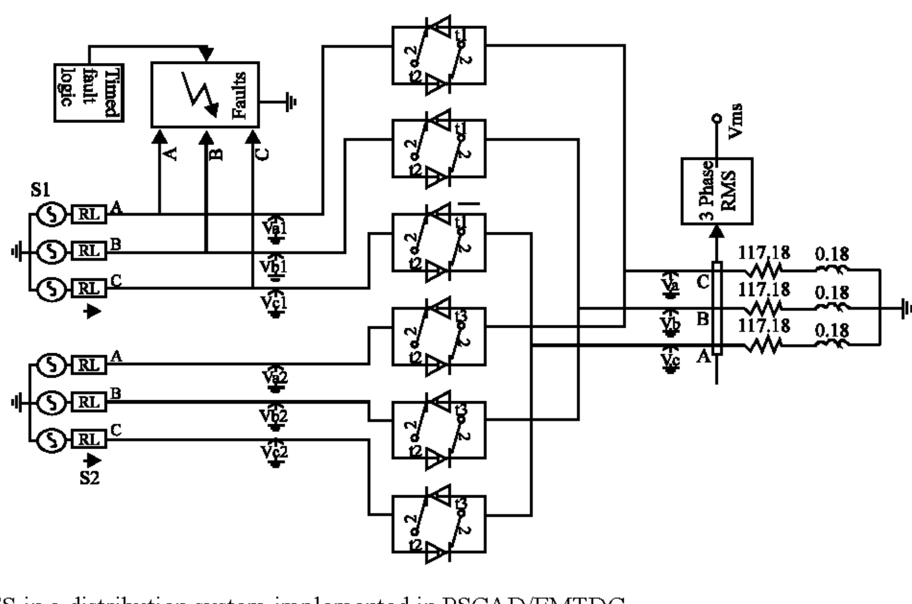

Fig. 3: The SSTS in a distribution system implemented in PSCAD/EMTDC

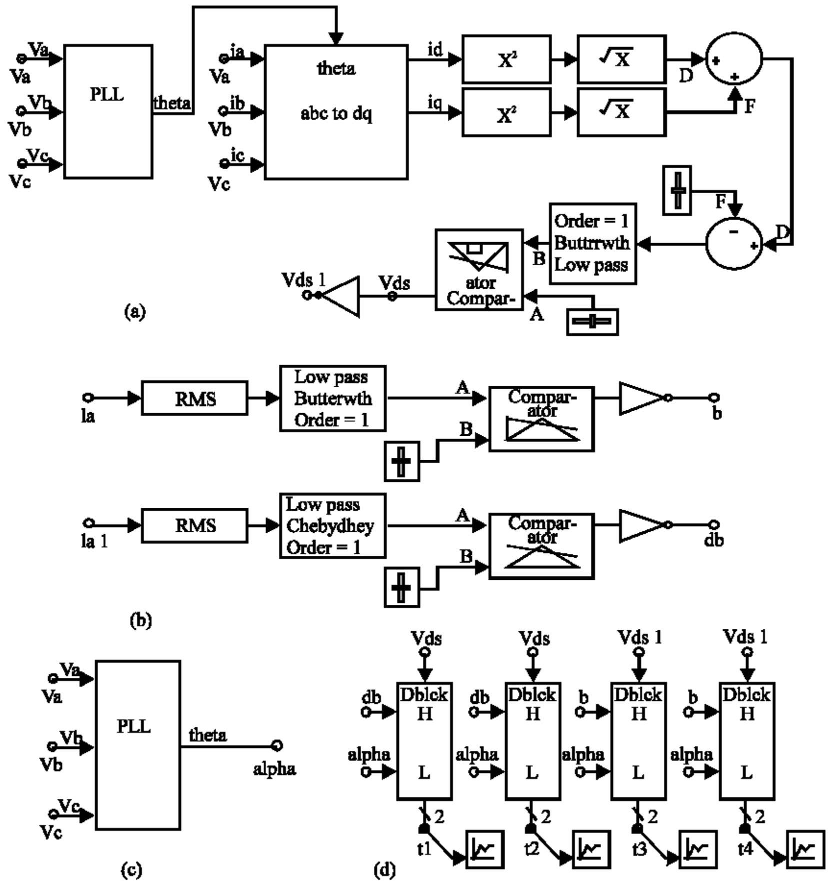

Fig. 4: Proposed control scheme of SSTS implemented in PSCAD/EMTDC

transformation block is the V_{dq} voltage vector in the reference frame that rotates in the power frequency. The voltage vector, V_{dq} is compared with a dc reference V_{ref} and an error is observed. The error is passed through a first order low pass filter to attenuate the impact of voltage transients. The filter introduces a delay to the error signal, which is determined by the filter cut-off frequency. The filter output is then compared to the voltage tolerance limit, V_{TL}. The output of the comparator is considered as the voltage detection transfer signal, which is used to initiate feeder transfer process when the main feeder fails.

Current detection: Figure 4b the current detection and zero crossing are responsible to either turn on or turn off the state of the thyristor switches and select the right switch to trigger in order to prevent source paralleling during the feeder transfer process. The system current is first passed through a smoothing first order low pass filter and then the output of the filter is compared with the zero current crossing threshold so as to generate a current detection signal.

PLL synchronizing scheme: The system voltages are fed to the three-phase PI controlled PLL as shown in Fig. 4c, in order to generate the synchronizing signal, which is the alpha value that synchronizes the voltage between the load and the feeder.

Firing control logic: The switching strategy of the firing control block with respect to voltage detection signal, current direction detection signal and PLL synchronizing signal, provides selective switching signals to the thyristor switches for fast load transfer process and prevents source paralleling as shown in Fig. 4d. The firing control logic generates selected switching signals for the main and backup feeder thyristor switches, based on the direction of current flow. When a fault or disturbance is detected on the main feeder, the thyristor switches of the main feeder are turned off and thyristor switches of the backup feeder are turned on. If one of the switches at the main feeder is conducting at the time of disturbance detection, then one switch of the backup feeder is gated and transfer process begins. If the commutation occurs and the main feeder current drops below zero while backup feeder current exceeds the zero current threshold, then both switches of the main feeder are turned off and the second switch of the backup feeder is also gated, thus the transfer process is completed. However, if commutation fails, the voltage across the incoming thyristor drops and the corresponding line current are in opposite polarities. In such a case, commutation cannot begin until the backup feeder thyristor is forward biased.

SIMULATION RESULTS AND DISCUSSION

To assess the effectiveness of the SSTS, simulations were first carried out in transferring power from faulted main feeder to back up feeder to show the compensation capability of SSTS and effect of induction motor loads in an industrial plant in terms of transfer time. Then, the performance of the SSTS under various fault conditions and various types of loads are investigated. PSCAD/EMTDC electromagnetic transient package was used for in the simulation.

Voltage sag compensation capability of SSTS: In this simulation, initially, the SSTS is not connected and a three-phase fault is applied at the main feeder at a time 0.2 sec, for the duration of 0.1 sec. Figure 5a shows that during the fault period, the magnitude of load voltage drops from 0.99 to 0.50 p.u in which a voltage sags of 50% occurs. Figure 5b shows rms voltage at load side, when SSTS is in operation. In this simulation, the control system detected the faults condition of the main feeder. Whenever a fault condition is detected, triggering signal of thyristors of both feeders are reversed in position i.e., switch of main feeder is turn off and switch of backup feeder is turn on. Consequently, the main feeder transfers power to the backup feeder while the RMS load voltage is restored to 0.99 p.u from 0.50 p.u at fault period, shown in Fig. 5b. Thus, voltage sag is mitigated.

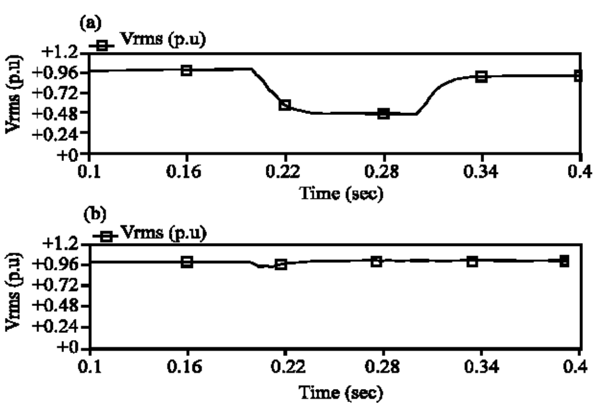

Fig. 5: Load voltage Vrms (p.u) a) without SSTS b) with SSTS connected

Effect of motor load in an industrial plant using SSTS: To illustrate the effect of induction motor loads on the operation of the SSTS, an industrial plant containing three induction motors has been analyzed. Base power of each induction motor considered is 1.2 MVA, 12.5 kV and 1450 rpm. A three phase to ground fault is simulated at time t_1 = 0.2 sec on the main feeder thus causing a 50% voltage sag for a duration of 0.1 sec as shown in Fig. 6a. Figure 6b shows that the load is transferred from the main feeder to the backup feeder due to successful operation of the SSTS and the system still remains in operation. Fig. 6c shows that the voltage sag is detected at time t_2 = 0.204 sec which result in a detection time (t_2- t_1) of 4 ms and the transfer process is completed at time t_3 = 0.212 sec, thus resulting in a transfer time (t_3- t_2) of 8 ms.

During voltage sag, an industrial motor tends to slow down and demands for higher current. Figure 7a shows that at the beginning of the 50% sag, the load current is higher and at the post fault sag, a much higher current is drawn by the motor while the voltage is being recovered, this is to rebuild the air gap flux and to reaccelerate the machine. This higher current may cause severe disturbances and motor may not be able to reaccelerate or may be tripped by protection devices. Result in Fig. 7b shows otherwise.

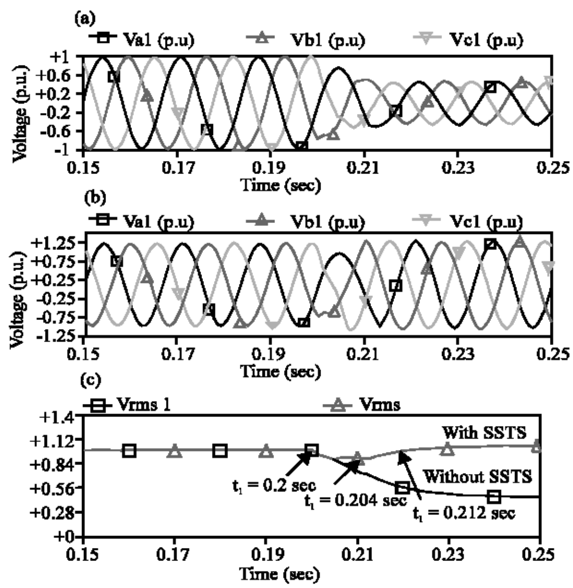

Fig. 6: Induction motor load voltage a) without SSTS b) with SSTS c) RMS voltage without and with SSTS

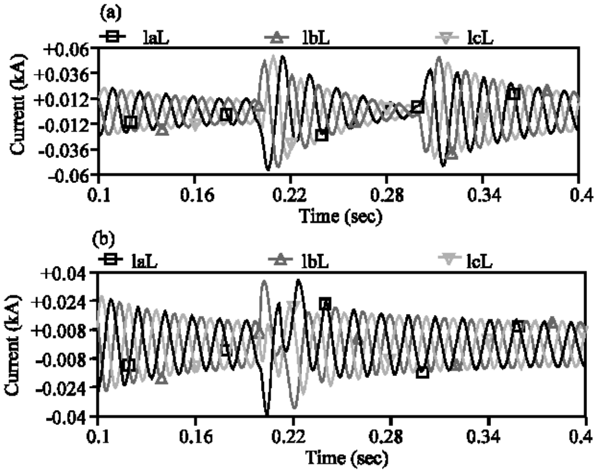

Fig. 7: Induction motor load current a) without SSTS b) with SSTS connected

Table 1: Summary of results of SSTS transfer times under various fault conditions and different load types

Load type	Fault type	DT (ms)	T T (ms)	IEEE B.T.T. (ms)
Static RL	3Φ to ground	0	3	3.05
,,	2Φ to ground	11	3	-
,,	Phase to phase	9	3	3.35
,,	Φ to ground	9	2.5	4.38
Ind. motor	3Φ to ground	4	8	-
,,	2Φ to ground	2	7.5	-
,,	Phase to phase	2	7	-
,,	Φ to ground fault	2	7	-
Hybrid	3Φ to ground f	10.5	3	8.23
,,	2Φ to ground fault	11	3.4	-
,,	Phase to phase	12	4	5.83
,,	Φ to ground	11	3	4.95

Having the SSTS in the circuit connection, the results showed successful operation. Load voltage is recovered within 8 ms while the load current resumes to its normal operating range as shown in Fig. 7b. Although at the beginning of the sag condition, the load current is slightly higher but it is still within the allowable range.

Investigation of solid state transfer switch under various operating condition: More simulations were carried out to investigate the performance of the SSTS under different load types and various fault conditions. The load types considered are the static RL load, induction motor load and combination of the static RL load and induction motor load known as the hybrid load. The various fault conditions are the three-phase to ground fault, double phase to ground fault, phase-to-phase fault and single phase to ground fault. In the simulations, all the faults are created at the main feeder whose X/R ratios are equal to one. The performance of the SSTS in terms of fault Detection Times (DT) and the Transfer Times (TT) under various fault conditions and different types of loads are summarized and tabulated as shown in Table 1. The transfer times obtained from the SSTS model using the proposed control system are compared with the transfer times obtained from the IEEE Benchmark STS-1 model.

Comparing the simulation results of the different types of loads, in terms of transfer times it can be seen that with static RL load, the SSTS performed faster load transfer as compared to with induction motor load and hybrid load due to the regenerative nature of induction motor. When an induction motor becomes regenerative, current flows from the induction motor to the main feeder and the air gap flux of the induction motor cannot instantly change, thus making the transfer of load from the main feeder to the backup feeder longer. However, in terms of detection times, the SSTS detects faults faster with induction motor load as compared to static RL load and hybrid load. This is due to the response of the voltage detection logic, which is mainly determined by the filter cut-off frequency. The higher the filter cut-off frequency, the faster the detection circuit and the shorter the detection time will be. The filter cut-off frequency of the induction motor is higher, because induction motor introduces a higher delay error signal.

Comparing the simulation results of the proposed SSTS and the IEEE Benchmark SST-1 models in terms of transfer times, it can be seen that the SSTS model with the proposed control system performs faster load transfer as compared to the IEEE Benchmark STS-1 model in which the transfer times (BTT) are shorter. The results are compared for some cases because the simulation results of the IEEE Benchmark STS-1 model are obtained for these cases only.

The SSTS transfer time is also determined by the fault type. From the simulation results, it can be seen that the transfer times vary under various fault conditions. The variations of transfer times depend on the phase faults and the respective phase commutations. For example, for the single phase to ground fault, two of the phases will start commutation without delay while the third phase will fail to commutate. Once a commutation fails, the transfer process has to wait until zero crossing of the phase voltage occurs. Thus, transfer time depends on the fault types and the number of phases involved in the commutation process. The simulation results also show that in general the transfer times are longer when unbalanced faults occur as compared to balanced faults.

In sum, the SSTS performs much better load transfer as compared to electromechanical transfer switches, which are slow in switching operation. As mentioned earlier, the electromechanical transfer switch usually transfers load to a back up feeder within the time range of 6 to 36 cycles, but the SSTS as shown in this simulation can transfer the load in less than half cycle or 10 ms.

CONCLUSIONS

In this study the modeling and simulation of SSTS has been presented for distribution systems protection. The simulation model is developed using the electromagnetic transient program PSCAD/EMTDC and the developed control strategy is thoroughly verified. An improved control system has been designed for fast action of thyristor switches in which it is based on both the Park's transformation theory and the three-phase PI controlled PLL whereas IEEE Benchmark STS-1 control is based only on Park's transformation theory. In the proposed control system, by using the PLL, fast synchronizing and accurate firing logic signals can be obtained thus making the SSTS transfer response comparatively faster. It is proven from the simulations that the SSTS can effectively perform voltage sag compensation in a test distribution system. Load transfer capability was investigated based on the effect of induction motor loads in an industrial plant in terms of transfer time. Investigation on the performance of the SSTS under different load types has shown that in terms of transfer times, for the system with static loads, the SSTS performs faster load transfer as compared to the system with induction motor load and hybrid load. The proposed SSTS with a new control system has shown the capability to transfer load faster compared to the IEEE STS-1 Benchmark system. In addition, the performances of SSTS under various fault conditions have also shown that the SSTS performs faster load transfer during balanced fault as compared to during unbalanced faults.

ACKNOWLEDGMENT

The authors would like to thank the Malaysian Ministry of Science, Technology and Environment for funding this study through research grant IRPA: 02-02-02-0019.

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