Review on Solid-State Transfer Switch Configurations and Control Methods: Applications, Operations, Issues, and Future Directions

M. S. MOLLIK\textsuperscript{1}, M. A. HANNAN\textsuperscript{2}, (Senior Member, IEEE), P. J. KER\textsuperscript{2}, (Member, IEEE), M. FAISAL\textsuperscript{2}, M. S. A. RAHMAN\textsuperscript{2}, (Member, IEEE), M. MANSUR\textsuperscript{2}, (Member, IEEE), AND M. S. HOSSAIN LIPU\textsuperscript{3}

\textsuperscript{1}UNITEN R&D Sdn Bhd, Universiti Tenaga Nasional, Selangor 43000, Malaysia
\textsuperscript{2}Department of Electrical Power Engineering, College of Engineering, Universiti Tenaga Nasional, Kajang 4300, Malaysia
\textsuperscript{3}Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia

Corresponding author: M. A. Hannan (hannan@uniten.edu.my)
This work was supported in part by the Tenaga Nasional Berhad under UNITEN R & D Sdn. Bhd., Universiti Tenaga Nasional, under Project Code U-TD-RD-19-20.

ABSTRACT

Solid-state transfer switch (SSTS) becomes the most crucial technology for electric power transmission, distribution and control system. SSTS is useful in supplying the power to sensitive loads uninterruptedly and critical loads economically and efficiently. However, a few concerns could hamper the effectiveness of SSTS including voltage swell, sag, inappropriate structure, poor power factor and inefficient control methods. Hence, this paper comprehensively surveys the diverse SSTS topologies, applications, operations, issues, and future directions. The SSTS configuration, design, control system, benefits and shortcomings are discussed rigorously. A detailed comparative analysis of various SSTS are carried out concerning topologies, control operations and applications. In line with that, the different control models and schemes are narrated briefly. This paper also highlights existing challenges and issues before providing a few important future prospects to enhance the configuration and efficiency of SSTS. All the key information obtained from this review would be beneficial to the researchers and power system engineers to develop an advanced and efficient SSTS toward future performance enhancement.

INDEX TERMS

Solid-state transfer switch, operation, topologies, power distribution, control system, transfer time.

I. INTRODUCTION

The types of disruptions that occur in a power system can be classified as problems related to the quality of electricity caused by voltage dips and surges, lightning strikes and other interferences associated with the system. Recent studies identify solid-state transfer switch (SSTS) as a possible cost-effective solution to power quality problems [1]–[3], which has been used for control purposes only [4]–[7]. The elemental concept of SSTS application is presented in Fig. 1 which includes the couple of thyristor switches that help to perform power transmission from primary sources to alternative sources to prevent service interruption.

The associate editor coordinating the review of this manuscript and approving it for publication was Inam Nutkani\textsuperscript{1}.

Nevertheless, Thyristor has the drawbacks of having cooling and loss consumption in the conventional SSTS.

Generally, a SSTS consists of thyristor switch gadgets to enable the switching from an essential source to a substitute source to prevent power interference upon the detection of an insufficiency in control quality. However, a thyristor is not a perfect conductor and causes a few issues in terms of its utilization and the requirement for cooling in an ordinary SSTS. To resolve this issue, a progressed solid-state switch was created to exchange a novel crossover switch device, coming about in irrelevant misfortune utilization and disposing the required cooling hardware [8]–[10]. Thyristor- based SSTS has many advantages such as low costs and low conduction loss which can be compared with the gate-turn-off thyristor- or concatenated gate-commutated thyristor-based systems.
The natural thyristor commutation extends the entire transfer process [11]–[15]. A Thyristor-based SSTS is utilized because of a double power supply to secure delicate loads from voltage drops. If it is comparable with gate turn-turn thyristor, it can be said that thyristor is one of the most preferable applications due to lower losses indeed it depends on others for switching purposes. The traditional SSTS can maintain the transmission process because it can detect the voltage drop and thyristor switching which can take more than a quarter of a cycle [16]. For conventional SSTS, thyristor switching starts when voltage distinction occurs between the two feeders and the load power factor. In a few circumstances, the overall transmission time of a conventional SSTS may surpass 10 ms. When transmission time is long, it may obstruct sensitive loads which may disrupt the industry standards operation.

Pulse switching circuit has been incorporated into the thyristors on the essential feeder. It has been designed for faster switching and decreases transmission time. If short-term voltage drops occur, then the production process will be obstructed resulting in significant losses. The TBSS shown in Fig. 2 is used to protect sensitive loads due to voltage drop. When the voltage drop happens, the static transfer switch (STS) promptly transfers loads from failed primary feeder to the alternative feeder so that it can avoid interruption from critical loads. Gate turn-off thyristor (GTO) has more conductivity losses than thyristors and in general, these losses occur in medium voltage applications [17].

Voltage sag has become a very important issue in the quality of electricity in recent years. Unexpected voltage sag disrupts production processes or even damages equipment. Since most of the utility companies supply dual power to achieve control quality and credibility, the Thyristor-based SSTS is becoming a feasible solution because it can protect critical workloads from the power quality issues [19]–[23]. Thyristor-based SSTS have a lot of advantages such as low cost and low conductivity losses which can be compared with thyristor gate-switch system [24]. However, thyristor-based switching systems are dependent on load power factor. In addition, it relies on the depth of the voltage dips and voltage difference between the primary and alternative feeders and so on. This frequently extends the transfer process to be beyond a quarter of a cycle, which could be a common prerequisite for protection against voltage drop [20]. To solve this problem, pulse switched impulse commutation bridge solid state transformer (ICBSTS), which uses LC resonance to force thyristor switching. ICBSTS can perform load transfer immediately after detecting voltage dips and has significant advantage over conventional SSTS. The ICBSTS is implemented as a forced switch for each step on the main thyristors T1p and T1n, as shown in Fig. 3. It works only on one set of LC resonant circuits. This system typically requires two LC circuits for each phase [18], [24], [25].

Another issue that has addressed in this paper is the inrush current of the transformer on the load side after the SSTS load being switched. When a voltage dip occurs, the deformed stresses are superimposed on the transformer from the load side and leads to a DC bias in its magnetic flux [27]. The magnetic saturation and high inrush current often take place because of SSTS transmission [28]. If the exact moment of transmission of the line is not controlled, the flow of current surge can fluctuate from 2 to 6 (p. u.). Moreover, if there is a voltage drop during the transfer, the sensitive loads can be interrupted. A flow estimation circuit is designed to determine an appropriate point in time of transfer that causes a smaller DC bias of the magnetic flux, and then ICBSTS transmits at a precise point by forced switching [29], [30].

In this paper, the main issues related to the development of a high voltage, high-power SSTS and related state-of-art are reviewed. The goal of this review is to carry out a
comprehensive analysis of diverse SSTS topologies, applications, operations, issues, and future directions. Therefore, a comprehensive description, an outline of SSTS topology, overview, voltage sag detection, control system, updated details, main features, advantages, limitations, and related applications are the key contributions of this paper. In a nutshell, this review paper makes recommendations for the future SSTS performance enhancement to allow it to be extensively embraced in the energy market.

II. OVERVIEW OF THE SYSTEM
SSTS has dual-channel switches that work as an automatic switching device. It selects a single power source. When the normal voltage range operates, the loads are connected to the main power source. If the primary power source is not supplying sufficient power, the loads are transferred to alternative power source. The load switches automatically back to the main power source when the main power supply is restored. SSTS employs a switching mode that helps achieving uninterrupted power switching (UPS) between different power inputs, such as N + 1 redundant non-parallel UPS system, N + 1 redundant UPS system of various capacities, N + 1 redundant UPS. Different types of system, excess city power, excess city power and generator” [23], [31]–[34]. In general, SSTS consists of three main components, which are parallel fast switch (PS1, and PS2), an anti-parallel thyristor switch (TS1 and TS2), and a control switch (Q0, Q1, and Q2). The primary structure is shown in Fig. 4.

III. SSTS CONFIGURATIONS
SSTS can be implemented as a major issue and prime choice for optimal topology in agreement with the accessible innovation. Two commercial assertions are displayed in this area, and an unused one is proposed within the following. Two trade deals are selected because their topologies are considered more descriptive in the SSTS. [40], [41].

A. HYBRID SWITCH DEVICE
The mechanical and electronic configuration do not require cooling system. Additionally, there is no switching loss for both hybrid configurations. The electronic switching system consists of two thyristors positioned in an antiparallel configuration while the mechanical switch is parallel to the branch of thyristor. The hybrid switch consists of a thyristor switch (TH), a parallel switch (PS) and a surge arrestor (AR) for protecting the thyristors against overvoltage. A circuit diagram of the hybrid switch is shown in Fig. 5 and its main characteristics are shown in Table 1.

![FIGURE 4. SSTS block diagram [31].](image1)

During the regular operating time, the primary power source supplies power to the loads. Here, the parallel mechanical switch PS1 is shut down, the thyristor TS1 switch is off, and the power switch Q0 is turned off. When the main power supply experiences a voltage drop, amplitude value will exceed so that it can withstand sensitive loads. PS1 switch will turn off when the SSTS control system will send the command to the PS1 switch and it will run TS1 in-between conduction. The current instantly moves to the thyristor and there is hardly an electric arc when PS1 is opened. If an arc accidentally arises, it will soon go out due to the conductivity of the thyristor. At that point, the TS1 trigger signal has been eliminated so that the thyristor can turn off when the crossing of the current is zero. Subsequently, if the TS2 thyristor switch is on then another side is included within the conductivity, the reinforcement power starts to control the loads. The control system activates a near command to PS2 after a short balance period. At this point, Q2 is always closed, when the voltage is zero in between two switches. Therefore, without electric arc, the switch PS2 can be closed. Eventually, the TS2 trigger signal is disabled, and the switching cycle is terminated. When the SSTS needs to be controlled, the power switch Q1 or Q2 is used to supply the load without interruption [31], [35]–[38]. The typical SSTS switching time is 5 milliseconds (ms), so sensitive loads will not fail. SSTS is broadly utilized not only in the electrical industry but also in the petrochemical industry, computer and telecommunication centers, automation and security systems in buildings and some other terms [37], [39].

![FIGURE 5. Hybrid switch device [40].](image2)

Under normal conditions, the line currents are passed through a mechanical switch (PS) and accordingly the thyristors (TH) are turned off. When an opening operation is needed then the PS opens, and TH are activated at the same time. The PS is opened immediately after a fault is found and
TABLE 1. The SSB characteristics [40]

| Parameter             | Value                |
|-----------------------|----------------------|
| Rated voltage         | 15 kv                |
| Rated Current         | 600 A / 1,200 A      |
| Interrupting Current  | 12.5 kA / 125 kA     |
| Short Time Current    | 12.5 kA / 125 kA     |
| Cooling Method        | Natural Cooling      |
| Thyristors rating     | 12 kV, 1500 A, 5-inch wafer |
| Time Characteristics  | < 114 cycle          |

TH begins to move the line current which is blocked at the first zero crossing of the current.

B. SOLID STATE DISTRIBUTION BREAKER

Electric Power Research Institute (EPRI) and Westinghouse have collaborated to develop this type of SSTS switch. This switch is used with a GTO switch because GTO switching time is less than a half cycle. For higher fault currents and good protection coordination, a parallel silicon controller rectifier (SCR) switch is provided. The six GTO modules are designed for per phase as a group, where the voltage was around 13.8 KV. Each module is being designed to achieve current and voltage value of 3000 A and 4500 V, respectively. Even though the GTO devices are interrupted by the current after 30 Pi and this interruption time is shorter because of assistive devices. When the fault current reaches the maximum level then the GTO branch opens (3000 A). Two series-connected thyristors are used to implement the SCR branch, as shown in Fig. 6.

C. EIGHT-THYRISTOR-BASED TRANSFER SWITCH CONFIGURATION

The transfer switch configuration appeared in Fig. 7 indicates that phase A from the AC source is a corresponding phase for the gear selector. Alternatively, phases B and C of the alternating current source can also be selected as the reference phase. The selective reference phase does not affect the transition indispensable and limitations for the low-speed induction (LSI) topology because of the symmetricity with short-stator configurations. Nonetheless, the effects of alternative transmission switch configuration should be considered based on importance for the LSS topology. The eight SCRs are arranged into the AC and DC sources for the low-speed synchronous (LSS) topology which are selected both Phase B and phase C. Given the loss of conductivity in the switch, the configuration of the reference phase A is still preferable to the reference phase B. When the motor speed is low at that time the stator current in phase A is twice. Additionally, the stator current keeps the balance for phases B and C with the stator winding of the doubly fed machine (DFM). Therefore, placing SCR in the A phase not only requires a higher rated current, but also leads to higher conductivity losses. In conclusion, the A-phase switching topology as a reference has the best performance in terms of loss and smooth mode transition compared to the other two options in the LSS topology [38], [43].

Configuration of SSTS installation circuits depends upon several factors such as the availability of an existing alternative source, the size of critical loads, one or more vital loads, and cost-effectiveness. There are three standard SSTS circuit configurations, which are shown in Fig. 8. The dual-service configuration is the widest representation of the SSTS system. The critical load is delivered by the preferred source under normal power conditions. The voltage drop occurs at a preferential source when the fault direction is upstream. Additionally, the critical load is transferred in less than half a cycle from the alternative source. Bold lines are seen on the distribution routes. If an interruption occurs at source A, at that time the critical load feeder A opens. When the solid-state switch of the bus coupler closes, then the whole load is preserved via source B, with a minimum load effect. It is important to note that the switches on both feeders must be designed to withstand the total current of both loads [34], [44].

IV. SSTS OPERATION

A. SCR-BASED TRANSFER SWITCH OPERATION

The SCR based SSTS switching system is based on three topologies such as voltage sag, the flux estimator and the
thyristor gating logic, as depicted in Fig. 9. The synchronous reference frame transformation (SFR) is applied so that the positive sequence of primary feeder voltage can be determined. This is applicable to detect the voltage sag [45]–[48]. The voltage sag can be detected by this detection scheme according to the magnitude of the positive sequence variable. It is very important to develop the flux estimator so that it can estimate the flow connection of the load transformer. In addition, the transient value will be measured. When any voltage sag is observed, the gating logic of the thyristor uses the calculated flux linkage to determine an acceptable instant of load transfer time. Hence, when transient flux linkage is at the maximum, the controller sends a command, but this transient flux linkage relies on the pre-determined level.

### B. ECO-MODE OPERATION

The eco-mode of the UPS device under normal input conditions is shown in Fig. 10. Sensitive loads are powered directly from the network through the SSTS system. In addition, the rectifier must maintain a constant DC bus voltage, and the inverter remains constant in order to minimize the switching losses and conductivity loss.

The timeline of the transition process is depicted in Fig. 11. The voltage difference is measured in source 1 after that, the transmission process is initiated from feeder 1 to 2. This figure illustrates that, when the source 1 voltage decreases under VU, the controller sends a signal to the parallel switch (PSI) and a gate signal to the thyristors (TSI) at the same time. PSI impedes not only current but also arc voltage in-between the anode and cathode of the thyristor. If the thyristor’s arc voltage is biased then its direction could be positive, at the same time current must conduct and transmit from PSI to TS1. The gate signal TS1 stops after a short time, and the thyristor TS2 is applied with another gate signal. When the gate signal is selected at this time it is applied on the pair of antiparallel thyristors which is namely TS2.

This TS2 is connected with opposite side thyristor which is TS1. At this time TS2 starts switching and it conducts current to the load from feeder 2. Thus, both feeders immediately transmit power to the loads. If the current value of the thyristor is zero, the conductive thyristor TS1 will be turned off. This current value will get interrupted by feeder 1. The load is supplied from source 2 when this point is on. If the current

---

**FIGURE 8.** Bus connector circuit configuration [33].

**FIGURE 9.** Schematic diagram of the proposed system [13].

**FIGURE 10.** Transfer process from the eco-mode to the double-conversion mode when Forced commutation (FC) = 0 and Double-conversion mode (DM) = 0.

**FIGURE 11.** Time chart of a transfer operation [1].
M. S. Mollik et al.: Review on Solid-State Transfer Switch Configurations and Control Methods

supplies are completed, then the PS2 switch turns off and at that time TS2 switch receives current.

1) THREE PHASE STS SYSTEM

These type of three-phase SSTS systems are based on a power circuit and control-logic [1], [50], [51]. This SSTS is connected with two three-phase 11 kV sources. The composition of a three-phase load transformer and switchgear (11KV/0.44KV) is connected with the sources, where the sources are G1 and G2 respectively. The SSTS control system consists of a combination of voltage detection and gating strategies. The control circuit detects inputs voltage and current. Not only the voltage and current are required to interface with the device but also start the transmission process.

2) VOLTAGE DETECTION STRATEGY

The flowchart of a common detection technique based on the Park transform is shown in Fig. 12. The control flow diagram is classified as eco-mode, fault diagnosis, forced switching and double-conversion mode.

![Figure 12. Control flow chart [13].](image)

The three-phase voltages $V_a(t)$, $V_b(t)$ and $V_c(t)$ are transformed into a fixed bi-axial coordinate system instantaneously, which is called the $\alpha\beta$ coordinate system. This operational procedure of this system is expressed using the following equations [52].

$$
\begin{bmatrix}
V_a(t) \\
V_b(t) \\
V_c(t)
\end{bmatrix} = \frac{\sqrt{2}}{3}
\begin{bmatrix}
1 & \frac{-1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \\
10 & \frac{2}{\sqrt{3}} & \frac{2}{\sqrt{3}} \\
\sqrt{2} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
V_{\alpha}(t) \\
V_{\beta}(t) \\
V_0(t)
\end{bmatrix}
$$

(1)

$$
V_{dq} = \sqrt{V_d^2 + V_q^2}
$$

(2)

$$
\theta(t) = \theta(0) + \int_{0}^{t} \omega(\xi)d\xi
$$

(3)

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

(4)

where $V_0(t)$ is the zero-sequence voltage component, $\theta(t)$ is the angle of conversion which is used to estimate the amplitude of the power vector as indicated in Eq. (4). The transmission signal is working as an output of the comparator, which begins the transmission process in case the preferred source fails [53].

3) GATING STRATEGY

The gating strategy is based on three identical logic sets, as shown in Fig. 13. These logic sets are used for three-phase SSTS system. It provides selective gating schemes for GTO switches, resulting in fast load transfer and preventing source parallelization [54]. A selective gating pattern is used based on transmission signal. The gating circuit has two switches for turn on such as a preferred side and alternative side switch. If the transmission signal is low then the preferred side switch turns on and the alternative side switch is off.

![Figure 13. Gating scheme [52].](image)

V. SSTS CONTROL METHODS

An SSTS control system block diagram is shown in Fig. 14. The primary and secondary feeder’s voltage has been measured by voltage measurement circuits which are voltage sensing one (VS1) and voltage sensing two (VS2) respectively. In addition, the phase difference and voltage angle

![Figure 14. Control system block diagram [1].](image)
detection circuit monitor the phase and angle difference between the two sources. Controlled information is transmitted to the SSTS Supervisory Control Scheme (SCC) [55].

The transfer operation performs from feeder 1 to feeder 2 when the SCC sends a control signal to SU1 and SU2. If the preferred voltage departs from its source voltage, then pre-set voltage at the upper level (VU) or voltage at the lower level (VL) operate as a conditional basis. The difference in phase and angle between alternate source and preferred source is within the preset value [1], [9], [18], [56]–[58]. Alternative source voltage has limitations. A block measuring diagram of the voltage is shown in Fig. 15.

![FIGURE 15. Block diagram of voltage and phase detection [1].](image)

The voltage sensor measures the sense value (v) at each step which is separately proportional to the amplitude of the source voltage. The phase voltage \( V = v \sin \theta \) is previously phase shifted by 90 degree, and the value \( v \cos \theta \) is obtained. Then \( V \) is calculated using Eq. (5) [1].

\[
V = v \sin \theta \times \sin \theta + v \cos \theta \times \cos \theta \quad (5)
\]

### A. SRF CONTROLLER

The proposed controller synchronous reference frames (SRF) are shown in Fig. 16. When the primary feeder falls to reach the predetermined threshold level, at that time the controller is initiated the transmission process immediately. The synchronous conversion of the reference frame is used in various active design filters and motor drives applications [59]–[65].

![FIGURE 16. SRF based controller for solid state transfer switch [66].](image)

The voltages of the main feeders \( v_{pa}, v_{pb}, \) and \( v_{pc} \) are measured and converted into a synchronous de-qe frame.

### B. CONTROL STRATEGY OF SOFT TRANSFER

The three-phase SCRs are turned on and off based on the SSTS control system because of the peak value of inrush current is confined this process is called smooth transfer control. A particular fire control procedure is shown in Fig. 17.

![FIGURE 17. Firing control strategy of the soft transfer method [67].](image)

SCR-B and SCR-C start with a shot starting point \( \alpha_0 \) in line with the reference time. The engine starts in a two-phase linked state. SCR-A starts at an angle of \( \alpha_1A \), before ib and ic reach zero. The engine is entering a small three-phase state. When current reaches nearly 0 at that time SCR composer and SCR_B operate with C1C and I1B for the natural shutdown. Afterward, the angles of fire are adjusted after each half cycle and this sequence are repeated (\( \alpha_2A, \alpha_2C, \alpha_2B \)).

BC-ABC-ABC-ABC-CA-ABC are the three-phase link sequence before all SCRs with a finite response angle \([n]\) are activated (for example, in Fig. 14). Experimental results illustrate that when the initial angle of fire is 0, then this angle is used under a condition. In accordance with the control technique, consequent firing angles can be derived from the initial firing angle and are usually 60 degrees (\( \pi/3 \)) behind one another. However, calculating 00 has become difficult because the initial connection of the B-phase and C-phase is an asymmetric transient. The relationship between \( \alpha_0 \) and transient current is almost same. This relationship will not change under different conditions for the residual motor voltage.

### C. IMPULSE COMMUTATION BRIDGE SOLID-STATE TRANSFER SWITCH (ICBSTS) CONTROLLER

The impulse commutation bridge solid-state transfer switch (ICBSTS) control system is based on the detection of voltage sag and the gating control line commutation. The operating system will be able to detect voltage sags and then activates the impulse switch for quick line transfer within a quarter cycle. The Voltage sag detection scheme of the ICBSTS is presented in Fig. 18.

### D. SSTS IN HIGH VOLTAGE APPLICATIONS

To accommodate the high-power rating applications, SSTS can be configured in different ways. The three single-phase
SSTs can be employed in place of three phase matrix converter [68]. In another way, low voltage switching devices connected in series can be structured to handle high voltages. However, this method has drawbacks of high conduction loss [69]. To address the problems, modular multi-level converters (MMC) is designed where cells are connected in series on the high voltage (HV) side while low voltage (LV) side cells are connected in parallel [70]–[72]. This MMC offers several benefits such as lower harmonics and switching losses, improved efficiency and high fault handling capability. Nevertheless, MMC has drawbacks including large number of switches, increased size and cost [73], [74]. The construction of three-phase MMC topology with several submodules (SM) is shown in Fig. 19. A controllable voltage source and storage capacitor are used to design each SM of MMC.

VI. FASTER POWER TRANSFER TOPOLOGIES OF SSTS

A. SSTS TRANSFER OPERATION IN DUAL POWER

For a three-phase power supply system, a solid-state switch with two power supplies consists of six series thyristors (SCR), as shown in Fig. 20. A primary power supply is connected to three SCRs and an alternative power supply. The other side is connected to the critical load driven by the engine. Usually, the engine load is immediately moved to an alternate source to primary source so that any kind of malfunction does not occur.
It is important to say that the transient and peak values of the stator current are diversified. This difference can be established as a phase angle. The remaining voltage and the voltage of an alternative source have also phase angles. The highest starting current shows in the worst primary state $\theta = 180^\circ$, and the peak value reaches a value nearby to 70A [39], [80], [81].

### VII. APPLICATION OF SSTS IN THE DISTRIBUTION SYSTEM

#### A. STATE-OF-THE-ART TECHNOLOGY

This particular device is designed to control an ultraviolet lamp. The application’s details remain confidential at the present time. The topology of the major circuit is the well-known sequence block of LC discharge and parallel effect, which is shown in Fig. 23.

![Basic circuit topology](image)

When lamp is started, the switch blocks all shock voltage. It is around 15 kV during regular service, but it can go up to 30 kV for up to 100\(\mu\)s at the end of the life of the lamp when the lamp cycle life is not stuck. When the lamp voltage level is lower around 2 KV at this time lamp will be stabilized. When the prime capacitor charge reaches nearly 25 KV at this time the switch activates to initiate a discharge. After that, the lamp will calm down because of the high voltage. The current and voltage waves are generated when the discharge switch are turned on, which are shown in Fig. 24. Then this procedure is repeated at 30 Hz, as shown in Fig. 25.

Many potential uses include laser power supplies, electrostatic precipitators, water treatment, scraping and physics of high energy. The same concept may give ratings of up to 120 kA and 50 kV for such applications, depending on the requirements of the specific application. Solid-state solutions can offer some advantages in applications that require a long and reliable life (without the need for maintenance), high average current, and harsh environments” [83], [84].

#### B. FAULT ISOLATION AND LIMITATION

A control circuit to detect a power voltage failure is shown in Fig. 26. When the grid voltage ($V_{g, abc}$) is sensed at that time it is converted into the output of its synchronous link frame components ($V_{g, q}$, $V_{g, d}$), as represented in Fig. 27. Where $\omega$ denotes the frequency of the grid line. A digital filter is required to decrease the transient voltage jump and ripple voltage of 120 Hz caused by an unstable component of the sequence [80], [85]–[88]. SSTS is utilized to protect loads from fault current or limit fault current. This Solid-State Transfer Switch has narrated below.

![Fault detection in case of voltage drop or swelling](image)

#### C. INTERRUPTION OF LOAD CURRENT AND SHORT CIRCUIT

In this procedure, solid state breaker (SSB) is used not only in normal condition but also in fault condition to protect the load from the rapid current. The working principle of SSB acts as a
M. S. Mollik et al.: Review on Solid-State Transfer Switch Configurations and Control Methods

FIGURE 27. SSB or SSTS as a load or current breaker [90].

circuit breaker which protects the load from interrupt current. When the current value goes above from its predefined value then it works as a circuit breaker. SSB is basically formed depending on the thyristor or combining the components of thyristor and GTO which appears in Fig. 26 [91]–[93]. In case of beginning, the current streams in an ordinary state is shaped by GTO (since they have superior proficiency) which is being enacted by thyristor components.

Therefore, when the current crosses the specific limit, the GTO blocks this current because thyristor peak current is larger than GTO. During the first zero crossing, this current is disrupted by the thyristor. Automatic re-activation and security management can be implemented using SSTS which helps the distribution system to respond more quickly.

D. FAULTY CURRENT LIMITER
At this point, if the SSB is used for limiting the short circuit current then the subsequent protection device eliminates the fault. There are two methods, which is applied to GTO and thyristor. There are two parallel branches which are formed by GTO (Fig. 28). This method is used to detect fault current of branches. When the fault current switches from branch 1 to branch 2 (GTO to Thyristor), it will detect the fault current. The reactor is designed to limit the current level. The second approach involves the interruption of short-circuit current by controlling the angle of ignition of semiconductor devices [39], [94]–[96]. Two methods can be used at the same time. The thyristor-controlled switch 2 can withstand a limited current level of equal to 10-15 cycles in a typical application.

FIGURE 28. SSB or SSTS as a fault current limiter [97].

E. BUS TIE BREAKER
In this case, SSB (Fig. 29) is used to isolate the bus during a feeder failure and can be applied using GTO components.

F. SOLID STATE TRANSFER SWITCH OR STATIC TRANSFER SWITCH
The SSB shown in Fig. 30 is employed to transfer power supply from conventional power systems to an alternative power system when a failure is detected under current power circumstances. This switch operates rapidly such as within a few milliseconds because the load maintains standard operation time.

The comparative study of various SSTS topologies concerning voltage, power, control and application is presented in Table 2.

FIGURE 29. SSB as a communication switch [98].

FIGURE 30. SSB as SSTS or STS [99].

VIII. ISSUES AND CHANGES
A. POWER FACTOR OF LOAD
The force switch is closely connected with the load current. This close action depends on force switch performance. The waveforms of voltages and currents change with various power factors (PF). Once the forced switching begins at the input voltage, the unit PF inverter has a narrow integration process range to account for the resulting peak load currents, so that inadequate current dynamics leads to a long switching time. If the variation range is narrow, then it can be easily trigged to the margin of linear variation. However, if the load with PF = 0, then it lags for a wider modulation spectrum in order to balance the peak load current [113], [114]. Consequently, the inverter has the best-forced switching performance when the load current is lower than PF.

B. VOLTAGE SAG
The current and voltage waveforms for a normal grid and a voltage drop of 50% are shown in Fig. 31. If the
50% voltage decreases, the load currents and inverter voltages are decreased so that the inverter can provide more variation than the typical grid service. Therefore, when the load current decreases at that time, the required compensation current also reduces. Therefore, voltage sag makes a huge contribution to speeding up forced commutation.

**C. VOLTAGE SWELL**

The current and voltage waveforms for a regular network and a 20% power surge are shown Fig. 32. When the voltage jump is 20%, then the load currents and the inverter voltage are forced to increase; thus, the variation range is decreased related to the regular procedure of the grid. Therefore, the load current increases based on the required compensation current so that the efficiency of the voltage swell can be reduced for the forced commutation mechanism.

**IX. SSTS SYSTEM STRUCTURE**

The schematic diagram of the educational system is shown in Fig. 33 [12], [13], [16], [116]. The SSTS system is composed of:

- Two utility feeders where one feeder is the primary source and another one is a backup source.
- A voltage-sensitive load
- Either SSTS is connected with the load or the source.
- The quality of the source voltage is monitored by a controller. The controller operates as a load transfer when it is required.
FIGURE 31. The form of current and voltage (a) normal grid and (b) a voltage drops of 50% [115].

FIGURE 32. Waveform of current and voltage (a) normal grid and (b) 20% voltage drop [115].

The SSTS control system consists of a voltage recognition unit, as well as selective gating logic. It is the responsibility of the detection device to monitor the quality of source voltage. It will be started transferring processes when the primary source does not meet the requirements of the load voltage [13], [54]. The measurement method has been used based on the park transformation matrix where it is transforming ac voltage into a synchronously rotating frame. The Thyristor gating generation system is used as a selective gating strategy. It produces thyristor gating patterns throughout regular, transfer, and post-transfer time. The selective logic is dependent online currents path [117]–[120].

A. CONTROL UNIT STRUCTURE

The SSTS units keep communicating with one another while transferring from one feeder to another feeder, at that time two sources are positioned remotely. The control system properly determines the time when alternative SCRs are de-blocked [121]–[123]. A simple method is employed to accomplish this:

**Stage One:** The selective source supplies feeder during the SSTS at full conduction. Additionally, the backup source keeps in stand-by condition with interrupted pulses. The alpha of the SCR ignition angle of the chosen SSTS source is forwarded to an alternate SSTS source before transfer. This SSTS synchronizes of its firing circuit with the alpha, while its pulses will be blocked.

**Step Two:** At the desired location, a blocking signal will be provided that blocks firing pulses on the SCRs of the STS.

**Step Three:** The SCR’s of the selective side would be turned off at each of the next zero current crossings.

**Step Four:** Instantly the feeder voltage is controlled by the SSTS when it observes the alternating direction. The phase voltage in the power supply decreases up to zero and will stay there when the first SCR in the output SSTS is turned off [54], [118]–[124]. This termination state is detected by the SSTS controller.

The voltage and current waveforms of the SCR are shown in Fig. 34 for one phase and the gating signals. The synchronization signal has been generated depends on switching...
voltage while it will control the pulses and the alpha angle. The communication voltage can be exposed to zero angle due to delay. The same alpha angle is applied at both sides to avoid conflicting current during feeder transmission. The detection time corresponds to the attenuation time of the thyristors, which ensures that there is no inrush current at the time of transmission [127]–[129].

X. CONCLUSION AND SUGGESTIONS
The study provides a comprehensive idea of SSTS configurations, control methods, applications, operations, issues, and future directions. Several literatures on existing topologies and control methods have been discussed in this paper to dispense beneficial information for SSTS. The review also highlights on the SSTS operations, applications and existing issues. Rigorous analysis on the configuration suggest that the switches on the both feeders must be designed to withstand the load currents and optimal placement of the switches can provide the best performance in terms of loss and transfer time. However, very few researches have been found on SSTS which can reduce both the cost and transfer time. Different types and methods of SSTS operation are analyzed with regards to fault isolation, fault current limiter, switching time, and functional capabilities. From the existing control method perspective, it is apparent that the magnitude, duration and the phase angle of the current can be controlled by proper timing of switching signals. However, there are some limitations on the calculation asymmetric transient current. Thus, an advanced intelligent control method is essential to improve the SSTS technologies in future applications. Then, the performances of different SSTS techniques compared in terms of their capabilities in protecting sensitive load against fault conditions. Finally, key factors in terms of performance, safety, and insulation for the implementation of SSTS are defined.

The comprehensive review has provided some important and specific suggestions for the advancement and potential applications of SSTS technological development, for instance:

- More studies are required for the intensity of the fault current limiting device when the current waveforms are exceedingly affected by electrical distortion and load current changes quickly.
- The highlighted issues and challenges need to be resolved to satisfy the high-voltage, high-power and high-frequency operating specifications.
- The SSTS has experienced authenticity and faced numerous challenges in terms of its overall performance. Thus, an advanced SSTS structural model needs to develop based on voltage sag, voltage swell, fault current detection, number of components, and efficiency.
- The controller should be designed to ensure the load safety during switch transition to ensure that the sensitive loads can withstand with any kind of interruption under diverse operating conditions.
- The advanced voltage detection method can be implemented to minimize switching or transfer time. The impedance effect of the primary and secondary feeders should be minimized while the SSTS is in operation mode. The SSTS needs an advanced safety unit comprising the flexible control system, sufficient inductive filters, and to reduce the effects of the time latency.

Such guidelines will play an important role in developing and implementing advanced intelligent SSTS. Furthermore, it will provide a clear idea to the researchers and manufacturers about the SSTS control method and applications so that they can understand how to promote the future production of SSTS. Overall, this research can provide researchers and industrialists to obtain a pathway for the future development of SSTS.

REFERENCES
[1] M. Takeda, H. Yamamoto, Y. Hosokawa, and I. Kamiyama, “A low loss solid-state transfer switch using hybrid switch devices,” in Proc. 3rd Int. Power Electron. Motion Control Conf. (IPEMC), Beijing, China, vol. 1, Aug. 2000, pp. 235–240.
[2] X. She, R. Burgos, G. Wang, F. Wang, and A. Q. Huang, “Review of solid state transformer in the distribution system: From components to field application,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Sep. 2012, pp. 4077–4084.
[3] X. She, “Control and design of a high voltage solid state transformer and its integration with renewable energy resources and microgrid system,” Ph.D. dissertation, Dept. Elect. Eng., North Carolina State Univ., Raleigh, NC, USA, 2013.
[4] Y. Hayashi, Y. Matsugaki, T. Ninomiya, and H. Ohashi, “Active gate controlled SiC transfer switch for fault tolerant operation of ISOP multicellular DC–DC converter,” in Proc. IEEE Int. Conf. Power Electron., Drives Energy Syst. (PEDES), Dec. 2016, pp. 1–6.
[5] X. Zhang, Y. Xu, Y. Long, S. Xu, and A. Siddique, “Hybrid-frequency cascaded full-bridge solid-state transformer,” IEEE Access, vol. 7, pp. 22118–22132, 2019.
[6] L. Olatomiwa and R. Olufadi, “Design and development of a low cost automatic transfer switch (ATS) with an over-voltage protection,” J. Multidisciplinary Eng. Sci. Technol., vol. 1, no. 4, pp. 190–196, 2014.
[7] A. Banerjee, S. B. Leeb, and J. L. Kirtley, “Performance comparison of transfer switch topologies in switched-doubly-fed machine drives,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Mar. 2016, pp. 2881–2888.
[8] J. P. Hopwood and J. W. Ciszek, “Solid state and surface effects in thin-film molecular switches,” Photochem. Photobiol. Sci., vol. 16, no. 7, pp. 1095–1102, 2017.
[9] G. Ortiz, M. G. Leibl, J. E. Huber, and J. W. Kolar, “Design and experimental testing of a resonant DC–DC converter for solid-state transformers,” IEEE Trans. Power Electron., vol. 32, no. 10, pp. 7554–7562, Oct. 2017.
[10] C. K. Amuzvi and E. Addo, “A microcontroller-based automatic transfer switching system for a standby electric generator,” Ghana Mining J., vol. 15, no. 1, pp. 85–92, 2015.

[11] H. Mokhtari, S. B. Dewan, and M. R. Travani, “Performance evaluation of thyristor based static transfer switch,” IEEE Trans. Power Del., vol. 30, no. 3, pp. 960–966, Jul. 2000.

[12] H. Mokhtari, S. B. Dewan, and M. R. Iravani, “Effect of regenerative load on a static transfer switch performance,” IEEE Trans. Power Del., vol. 16, no. 4, pp. 619–624, Oct. 2001.

[13] M.-J. Tsai, Y.-Y. Shen, J. Zhou, and P.-T. Cheng, “A forced commutation method of the solid-state transfer switch in the uninterrupted power supply applications,” IEEE Trans. Ind. Appl., vol. 56, no. 2, pp. 1609–1617, Mar. 2020.

[14] M.-J. Tsai, Y.-F. Liou, and P.-T. Cheng, “Active harmonic filtering with a low switching frequency inverter,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Mar. 2019, pp. 713–720.

[15] M. V. M. Rodrigues, N. da Silva, and F. A. S. Gonçalves, “Static transfer switch applied to single-phase uninterruptible power supply,” in Proc. IEEE 15th Brazilian Power Electron. Conf., 5th IEEE Southern Power Electron. Conf. (COBESP/SPEC), Dec. 2019, pp. 1–6.

[16] G.-H. Gwon, C.-H. Kim, Y.-S. Oh, C.-H. Noh, T.-H. Jung, and J. Han, “Mitigation of voltage unbalance by using static load switch in bipolar low voltage DC distribution system,” Int. J. Electr. Power Energy Syst., vol. 90, pp. 158–167, Sep. 2017.

[17] H. H. De Silva, D. K. Jayamaha, and N. W. Lidula, “Review on design and control of solid-state transformer based microgrids,” AIMS Energy, vol. 7, no. 6, pp. 901–923, Nov. 2019.

[18] T. Zhang, “High peak current MOS gate-triggered thyristor with fast region control scheme for suppressing cross current in static transfer switch,” in Proc. 10th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG), Xi’an, China, Jun. 2019, pp. 1036–1402.

[19] J. W. Schwartzenberg and R. W. De Doncker, “15 kV medium voltage static transfer switch,” in Proc. IEEE Ind. Appl. Conf. 30th IAS Annul. Meet. (IAS), vol. 3, Oct. 1995, pp. 2515–2520.

[20] A. Sannino, “Static transfer switch: Analysis of switching conditions and accent transfer transition,” in Proc. IEEE Power Eng. Soc. Winter Meeting, vol. 1, Jan. 2001, pp. 120–125.

[21] J. Yoo, A. Abramovitz, Y. Wang, W. Meng, and J. Zhao, “Safe-triggering-region control scheme for suppressing cross current in static transfer switch,” Electr. Power Syst. Res., vol. 1, pp. 245–253, Aug. 2015.

[22] W. Chen, C. Liu, X. Tang, L. Lou, W. Cheng, Q. Zhou, Z. Li, and B. Zhang, “High peak current MOS gate-triggered thyristor with fast turn-off characteristics for solid-state closing switch applications,” IEEE Electron Device Lett., vol. 37, no. 2, pp. 205–208, Feb. 2016.

[23] A. Kumar, M. T. Otley, F. A. Alamar, Y. Zhu, B. G. Arden, and G. A. Sotzing, “Solid-state electrochromic devices: Relationship of contrast as a function of device preparation parameters,” J. Mater. Chem. C, vol. 2, no. 14, pp. 2510–2516, 2014.

[24] C. Meyer and R. W. De Doncker, “Solid-state circuit breaker based on active thyristor transfer devices,” IEEE Trans. Power Electron., vol. 21, no. 2, pp. 450–458, Mar. 2006.

[25] S. Schroder, C. Meyer, and R. W. De Doncker, “Solid-state circuit breakers and current-limiting devices for medium-voltage systems,” in Proc. IEEE Int. Power Electron. Congr. (CIEEP), Oct. 2002, pp. 91–95.

[26] P.-T. Cheng and Y.-H. Chen, “Design of an impulse commutation bridge for the solid-state transfer switch,” IEEE Trans. Ind. Appl., vol. 44, no. 4, pp. 1249–1258, Jul. 2008.

[27] H. Mokhtari, M. R. Iravani, and S. B. Dewan, “Transient behavior of load transformer during subcycle bus transfer,” IEEE Trans. Power Del., vol. 18, no. 4, pp. 1342–1349, Oct. 2003.

[28] B.-C. Kim, Y.-H. Chung, H.-D. Hwang, and H.-S. Mok, “Development of HVDC circuit breaker with fast interruption speed,” in Proc. 9th Int. Conf. Power Electron. ECCE Asia (ICPES-ECCE Asia), Jun. 2015, pp. 2844–2848.

[29] J. Schwartzenberg, “Application of AC switch power electronic building blocks in medium voltage static transfer switches,” in Proc. IEEE Power Eng. Soc. Gen. Meeting, vol. 3, Jul. 2003, pp. 1372–1374.

[30] R. E. Brown and J. R. Ochoa, “Impact of subcycle transfer switches on distribution system reliability,” IEEE Trans. Power Syst., vol. 15, no. 1, pp. 442–447, Feb. 2000.

[31] S. C. Wang, G. F. Tang, K. S. Yu, and J. C. Zheng, “Development of a novel medium voltage solid state transfer switch,” Power Syst. Technol., vol. 31, no. 2, pp. 311–315, 2006.
O. F. Kececioglu, H. Acikgoz, and M. Sekkeli, “Advanced configuration
S. Bhattacharya, P.-T. Cheng, and D. M. Divan, “Hybrid solutions for
M. Takeda and S. Jochi, “Development of advanced solid-state transfer
A. M. Zungeru, “Design of a smart embedded uninterrupted power supply
N. F. Y. Mohamed, “Design of smart switch for choosing different power
J. Commerton, M. Zahzah, and Y. Khersonsky, “Solid state transfer
J. Lu, M. Savaghebi, S. Golestan, J. C. Vasquez, J. M. Guerrero, and
X. She, A. Q. Huang, and R. Burgos, “Evaluation of solid-state transfer transformers technologies and their application in power distribution systems,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 7, no. 3, pp. 510–521, Sep. 2019.

T. Elavarasan, S. Chandrasekar, and R. Mathiyazhagan, “Designing and simulation of power electronic solid state circuit breaker for medium voltage transmission line protection,” Adv. Natural Appl. Sci., vol. 11, no. 8, pp. 457–465, Jun. 2017.

J. G. Horstmann, B. Wit, G. Stroock, and C. Ropers, “Coherent control of a structural phase transition in a solid-state surface system,” J. Magn. Magn. Mater., vol. 446, pp. 419–422, Jun. 2017.

A. Abu-Siada, J. Budiri, and A. F. Abdou, “Solid state transformers: comparison of iron core and solid state transformers,” IEEE Trans. Power Electron., vol. 30, no. 6, pp. 3623–3631, Jun. 2015.

J. Lu, M. Savaghebi, S. Colestan, J. C. Vasquez, J. M. Guerrero, and A. Marzabal, “Multimode operation for on-line uninterruptible power supply system,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 7, no. 2, pp. 1181–1196, Jun. 2019.

J. Commerton, M. Zahzah, and Y. Khersonsky, “Solid state transfer switches and current interruptors for mission-critical shipboard power systems,” in Proc. IEEE Electr. Ship Technol. Symp., Philadelphia, PA, USA, Jul. 2005, pp. 298–305.

N. F. Y. Mohamed, “Design of smart switch for choosing different power sources,” Ph.D. dissertation, Univ. Gezira, Wad Madani, Sudan, 2018.

A. M. Zungeru, “Design of a smart embedded uninterruptible power supply system for personal computers,” Int. J. Embedded Syst. Appl., vol. 2, no. 4, pp. 1–19, Dec. 2012.

M. Takeda and S. Jochi, “Development of advanced solid-state transfer switch using novel hybrid switch devices,” in Proc. 6th Int. Conf. Adv. Power Syst. Control. Oper. Manage., China, 2003, pp. 535–540.

R. Balasubramanian and S. Palani, “Simulation and performance evaluation of shunt hybrid power filter for power quality improvement using PQ theory,” Int. J. Electr. Comput. Eng., vol. 6, no. 6, pp. 2603–2609, Dec. 2016.

O. F. Kececioglu, H. Acikgoz, C. Yildiz, A. Gani, and M. Sekkeli, “Power quality improvement using hybrid passive filter configuration for wind energy systems,” J. Electr. Eng. Technol., vol. 12, no. 1, pp. 207–216, Jan. 2017.

O. F. Kececioglu, H. Acikgoz, and M. Sekkeli, “Advanced configuration of hybrid passive filter for reactive power and harmonic compensation,” SpringerPlus, vol. 5, no. 1, pp. 1–20, Dec. 2016.

W. U. K. Tareen and S. Mekhilef, “Three-phase transformerless shunt active power filter with reduced switch count for harmonic compensation in grid-connected applications,” IEEE Trans. Power Electron., vol. 33, no. 6, pp. 4868–4881, Jun. 2018.

S. Bhattacharya, P.-T. Cheng, and D. M. Divan, “Hybrid solutions for improving passive filter performance in high power applications,” IEEE Trans. Ind. Appl., vol. 33, no. 3, pp. 732–747, May 1997.

S. R. Das, P. K. Ray, A. Mohanty, and T. K. Panigrahi, “Application of artificial intelligence techniques for improvement of power quality using hybrid filters,” in Computational Intelligence in Data Mining, Singapore: Springer, 2020, pp. 719–729.

A. K. Mishra, S. R. Das, P. K. Ray, R. K. Mallick, A. Mohanty, and D. K. Mishra, “PSO-GWO optimized fractional order PID based hybrid shunt active power filter for power quality improvements,” IEEE Access, vol. 8, pp. 74497–74512, 2020.

P.-T. Cheng and C.-H. Tsai, “An improved solid-state transfer switch controller for sensitive industrial loads,” in Proc. IEEE Power Eng. Soc. Gen. Meeting, vol. 4, Jul. 2003, pp. 2514–2519.

X. Cui, Z. Zhang, H. Zhao, L. Zhang, X. Zhao, and J.-S. Lai, “SSTS-based soft transfer control method of motor load under different residual voltage condition,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Montreal, QC, Canada, Sep. 2015, pp. 1075–1080.

Z. Zhang, H. Zhao, S. Fu, J. Shi, and X. He, “Voltage and power balance control strategy for three-phase modular cascaded solid state transformer,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Mar. 2016, pp. 1475–1480.

X. She, A. Q. Huang, and R. Burgos, “Review of solid-state transformer technologies and their application in power distribution systems,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 1, no. 3, pp. 186–198, Sep. 2013.

S. Bifaretti, P. Zanchetta, A. Watson, I. Taricciotti, and J. C. Clare, “Advanced power electronic conversion and control system for universal and flexible power management,” IEEE Trans. Smart Grid, vol. 2, no. 2, pp. 231–243, Jun. 2011.

H. A. Hamed, A. F. Abdou, S. Acharya, M. S. El Moursi, and E. E. El-Kholy, “A novel dynamic switching table based direct power control strategy for grid connected converters,” IEEE Trans. Energy Convers., vol. 33, no. 3, pp. 1086–1097, Sep. 2018.

H. A. Hamed, A. F. Abdou, E. H. E. Bayoumi, and E. E. El-Kholy, “A fast recovery technique for grid-connected converters after short dips using a hybrid structure PLL,” IEEE Trans. Ind. Electron., vol. 65, no. 4, pp. 3056–3068, Apr. 2018.

M. A. Hannam, P. J. Ker, M. S. H. Lipu, Z. H. Choi, M. S. A. Rahman, K. M. Muttaqi, and F. Blaabjerg, “State of the art of solid-state transformers: Advanced topologies, implementation issues, recent progress and improvements,” IEEE Access, vol. 8, pp. 19113–19132, 2020.
M. J. Adams, M. Verosky, M. Zebardjadi, and J. P. Heremans, “High switching ratio variable-temperature solid-state thermal switch based on thermoelctrics,” Int. J. Heat Mass Transf., vol. 134, pp. 114–118, May 2019.

R. B. Jeyaprada and V. Rajini, “Small signal averaged transfer function model and controller design of modular solid state transformers,” I&I Trans., vol. 84, pp. 271–282, Jan. 2019.

H.-J. Choi, H.-P. Park, and J.-H. Jung, “Design methodology of dual active bridge converter for solid state transformer application in smart grid,” in Proc. 9th Int. Conf. Power Electron. ECCE Asia (ICPE-ECCE Asia), Seoul, South Korea, Jun. 2015, pp. 196–201.

P. Cairoli, L. Qi, C. Tschida, V. R. R. Ramanan, L. Raciti, and A. Antoniazzi, “High current solid state circuit breaker for DC shipboard power systems,” in Proc. IEEE Electric Ship Technol. Symp. (ESTS), Aug. 2019, pp. 468–476.

S. A. M. Saleh, C. Richard, X. F. S. Onge, K. M. McDonald, E. Ozkop, L. Chang, and B. Alsadyi, “Solid-state transformers for distribution systems—Part I: Technology and construction,” IEEE Trans. Ind. Appl., vol. 55, no. 5, pp. 4524–4535, Oct. 2019.

F. Ruiz, M. A. Perez, J. R. Espinosa, T. Gajowik, S. Stynski, and M. Malinowski, “Surveying solid-state transformer structures and controls: Providing highly efficient and controllable power flow in distribution grids,” IEEE Ind. Electron. Mag., vol. 14, no. 1, pp. 56–70, Mar. 2020.

T. Ise, M. Takami, and K. Tsuji, “Hybrid transfer switch with fault current limiting function,” in Proc. 9th Int. Conf. Harmon. Qual. Power, Orlando, FL, USA, vol. 1, Oct. 2000, pp. 189–192.

C. Peng, X. Song, M. A. Rezaei, X. Huang, C. Widener, A. Q. Huang, and M. Steurer, “Development of medium voltage solid-state fault isolation devices for ultra-fast protection of distribution systems,” in Proc. 40th Annu. Conf. IEEE Ind. Electron. Soc. (IECON), Dallas, TX, USA, Oct. 2014, pp. 5169–5176.

J. Wu, J. Xu, and D. Lv, “Optimal design of the mechanical switch suitable for the ATS,” J. Eng., vol. 2019, no. 16, pp. 2589–2592, Mar. 2019.

S. A. Tsyruk, S. I. Gamazin, Y. N. Ryzhkova, and K. F. Charafeddine, “Determination of source fault using fast acting automatic transfer switch,” in Proc. Dyn. Syst., Mech. Mach. (Dynamics), Omsk, Russia, Nov. 2018, pp. 1–4.

C. Li and T. Shengxue, “Solid-state AC breaker with parallel switched capacitor circuits for microgrid system,” J. Chin. Inst. Eng., vol. 42, no. 8, pp. 748–756, Nov. 2019.

M. Hannan, A. Mohamed, and H. Aini, “A simulation model of solid-state transfer switch for protection in distribution systems,” J. Appl. Sci. vol. 6, no. 9, pp. 1993–1999, Sep. 2006.

M. R. Javed, T. Mahmood, and M. A. Choudhry, “Performance analysis of static transfer switch using MATLAB/simulink,” in Proc. Power Gener. Syst. Renew. Energy Technol. (PGSRET), Islamabad, Pakistan, Jun. 2015, pp. 1–5.

J. A. Fereiro, “A solid-state protein junction serves as a bias-induced current switch,” Angew. Chem. Int. Ed., vol. 58, no. 34, pp. 11852–11859, Jan. 2019.

H. Mokhtari, S. B. Dewan, and M. R. Iravani, “Analysis of a static transfer switch with respect to transfer time,” IEEE Trans. Power Del., vol. 17, no. 1, pp. 190–199, Jan. 2002.

P.-T. Cheng and C.-H. Tsai, “An improved solid-state transfer switch controller for sensitive industrial loads,” in Proc. IEEE Power Eng. Soc. Gen. Meeting, Toronto, ON, Canada, Jul. 2003, pp. 1–6.

X. Zhang, Y. Xu, A. Siddique, Y. Long, and X. Xiao, “A microprocessor resource-saving dual active bridge control for startup and restart of three-stage modular solid-state transformer,” IEEE Trans. Power Del., vol. 35, no. 3, pp. 1443–1454, Jun. 2020.

B. Tian, C. Mao, J. Lu, D. Wang, Y. He, Y. Duan, and J. Qiu, “400 V/1000 kVA hybrid automatic transfer switch,” IEEE Trans. Ind. Electron., vol. 60, no. 12, pp. 5422–5435, Dec. 2013.

T. Mahmood and M. A. Choudhry, “Performance improvement of complementary feeders using static transfer switch system,” J. Zhejiang Univ.-Sci. A, vol. 10, no. 2, pp. 189–200, Feb. 2009.

M. S. Mollik et al.: Review on Solid-State Transfer Switch Configurations and Control Methods

182505

VOLUME 8, 2020