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AC-AC Solid-State Distribution Transformer

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SUMMARY

The transformer is a key component of the electrical system that transfers electrical energy from one electrical circuit at one voltage to another voltage through the process of electromagnetic induction. Solid-State Transformers (SST) are an emerging technology that is rapidly growing and has been regarded as a ground-breaking innovation to replace the century-old bulky conventional transformers with a lighter, smaller, and smarter architecture. This paper shows one possible approach of AC-AC power transformation using pure solid-state switches and passive components without an intermediate magnetically-based transformer. It is based on the concept of capacitor-based transformation of power from one voltage level to another. It offers some useful features: (1) internal redundancy sufficient to obviate the need for the spare transformer normally supplied with magnetic transformation, (2) absence of toxic insulating oil, (3) ease of manufacture, being modular in construction, (4) inherent phase-shifting capability, and (5) the ability to convert between primary and secondary nodes differing in frequency and/or wave-shape. The new architecture enriches the existing SST family and introduces a configuration that requires fewer converter stages. The simulation results will show that the proposed SST can transform one AC voltage to another AC voltage using pure solid-state devices and be bi-directional, exactly as a magnetically-based conventional transformer, but with even more functions, such as fast and dynamic control over the output voltage, and fully controllable output power by shifting the phase angle of the transformer output voltage. In addition, the grid side reactive power can be controlled. Another unique feature is to use the resonant circuits for soft switching (zero-current switching) while charge exchanging between the first node and the transformer, and between the second node and the transformer. The total DC voltage of the submodule (SM) column is stable, and the individual SM capacitor voltage is sorted and balanced. The over-current protection mechanism detects faults and isolates the transformer. The results will successfully demonstrate that the proposed distribution SST is a pure solid-state transformer that only uses a single converter stage and no magnetically-based transformer but still has the function of the conventional transformer, as well as it provides additional features that can contribute to the future smart distribution grid.

KEYWORDS

Solid-State Transformer, Resonant, Capacitor-based Power Transformation, AC-to-AC Conversion

1. BACKGROUND AND INTRODUCTION:

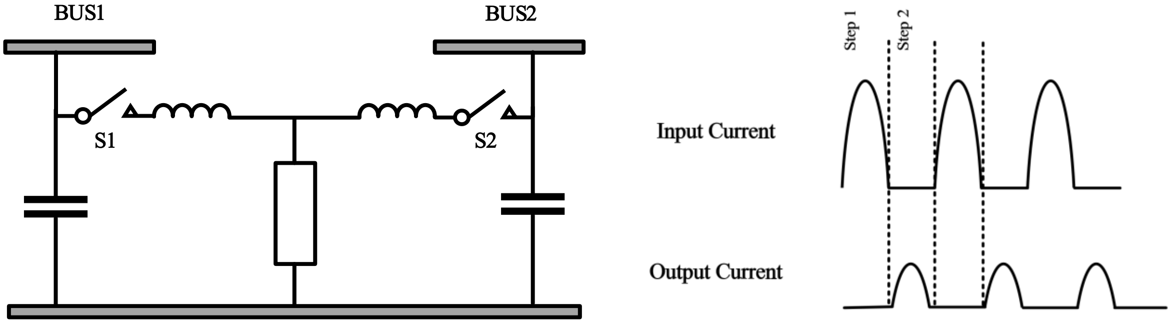
The earliest concept of solid-state transformer was introduced by William McMurray in 1970 [1], and several contributions were made in the 80s and 90s [2-4]. However, at that time the development of SST was limited by its voltage rating and the switching device. Over the last two decades, the technology being more and more mature, several topologies were demonstrated with high efficiency and high switching frequency therefore small physical size. At the same time, the increasing integration of distributed energy resources and electric vehicles, as well as an aging distribution infrastructure, all of which challenges the management of the distribution grids and leads to an extensive infrastructure upgrade. The SST does not only perform the voltage conversion function, but it also provides other services to the distribution grid, such as voltage and power flow control, power quality improvement. With the variety of SST topologies that have been proposed, the most commonly studied is the Three-Stage SST, which includes an AC-DC converter, a Dual-Active Bridge (DAB) DC-DC converter, and a DC-AC converter.

This paper proposed a new SST topology to achieve AC-AC power transformation that only uses a single-stage power converter, which minimizes the number of power switches and passive components. The proposed SST is based on the principle of capacitor-based power transformation, which was applied to an early study in 2015 of a DC-DC direct transformation case that connects two large HVDC [5]. In late 2019, studies were started to investigate the ability to employ such a concept in AC-AC power transformation.

The proposed SST system [6] transforms the voltage of AC electrical energy by resonant charge between a first node and a second node. This SST was modeled in detail using an EMT simulator to assure operation following the principles. A 14.4 kV/0.347 kV 167 kVA single-phase solid-state transformer case is studied, which is one phase of a 500 kVA, 25kV/600V pad mount distribution transformer.

2. CAPACITOR-BASED POWER TRANSFORMATION:

The basic architecture of Capacitor-based Power Transformation consists of a single column of series-connected capacitors, two high-frequency resonant circuits, two bi-directional switches, and passive smoothing inductors, as shown in Fig. 1 (a). Energy exchange between multiple electrical nodes by high-speed, repetition of the three-step process. The first step being a resonant half-cycle exchange of energy between a first voltage node and a column of series-connected capacitors. The second step being electrical reconfiguration of capacitors within the series-connected column, and the third step being a resonant half-cycle exchange of energy between the reconfigured column and one or more secondary nodes.



(a) (b)

Figure 1. (a) an illustration of Capacitor-based Power Transformation, (b) the input and output current pulses

The core element of the SST is the series column of capacitive modules which is charged resonantly through a reactor from a primary bus and discharged resonantly through a different reactor to a secondary bus. The switching frequency of the main switches (S1 and S2) matches the resonant frequency so that zero-current switching (or soft-switching) can be achieved to minimize the switching losses. The SST achieves power transformation by alternately receiving a current pulse from one bus and delivering a current pulse to another through S1 and S2 as shown in Fig. 1 (b). The switches are bi-directional to allow current flow both ways. The control system reads the pre-set reference signals and sends instantaneous orders to the Sub-Modules (SM) to convert the capacitor's DC voltage to AC voltage. The SST also offers bi-directional power, which is a key feature to support the future smart grid. With the number of household solar panels and EV chargers increasing, the proposed SST allows customers to sell extra power generated from PV and use the EV battery to store energy during a non-peak period and send it back to the grid in peak period, known as "Peak Shaving" [7].

During the energy exchange between the first node (grid) and the capacitor column, the SST generates a regulated voltage based on the grid voltage magnitude and tracks the grid phase angle through a Phase-Locked Loop (PLL) to improve the power factor at the point of common coupling. During the communication with the grid, the SST acts as a cascaded modular multilevel STATCOM. The grid side reactive power is also controllable by adjusting the primary side voltage magnitude.

3. SOLID-STATE DISTRIBUTION TRANSFORMER

Topology

The single-phase Solid State Distribution Transformer (SSDT) applied the concept of capacitor-based power transformation. It is targeting the distribution level, where medium voltage and high turns ratio appears. To achieve high turns ratio power transformation while keeping the number of full-bridge Sub-Modules (SM) relatively low, a new configuration was developed as shown in Fig. 2. Instead of tapping the secondary side from the top of the SM column, this configuration taps it in the middle. In this case, the column of SMs is separated into two groups, the upper group is named MMC1, and the lower one is named MMC2. MMC1 holds a much higher DC voltage than MMC2. This is done by using different SM capacitance for each MMC and employing additional controls.

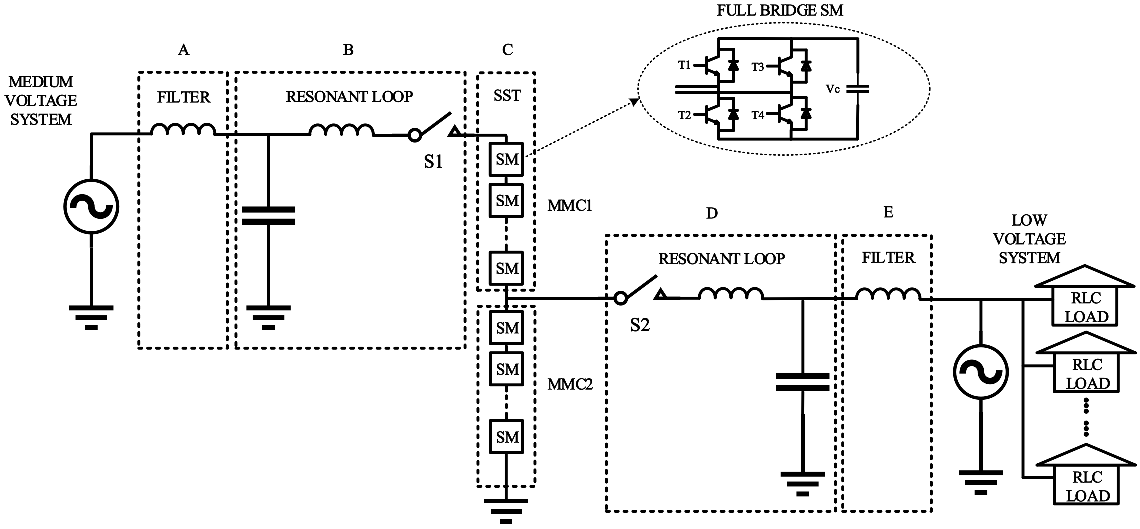


Figure 2. Block Diagram of the SSDT

There are two main switches located on each side of the SSDT, S1, and S2. They alternately switch on and off to allow power transformation from one end to another. When S1 is on, both MMC1 and MMC2 are connected to the primary bus. When S2 is on, only MMC2 is connected to the secondary bus. The column of capacitors uses a full-bridge structure to control the operations such as inserting, bypassing, or reversing the capacitor voltage of V_C, as illustrated in Fig 2. The resonant loops B and D have a resonant frequency of $f_r = \frac{1}{2\pi\sqrt{LC}}$, by selecting the LC size, we can make the switching frequency $f_s = f_r$, so S1 and S2 can be soft-switched to minimize the switching losses.

Control Blocks and Capacitor Sorting Block

The SSDT is equipped with several control blocks to ensure the proper operation and enhance the overall stability. The central control block shown in Fig. 3 includes (1) total capacitor voltage control, (2) primary side reactive power control, (3) secondary side output voltage control, (4) upper MMC capacitor voltage control, and (5) lower MMC capacitor voltage control.

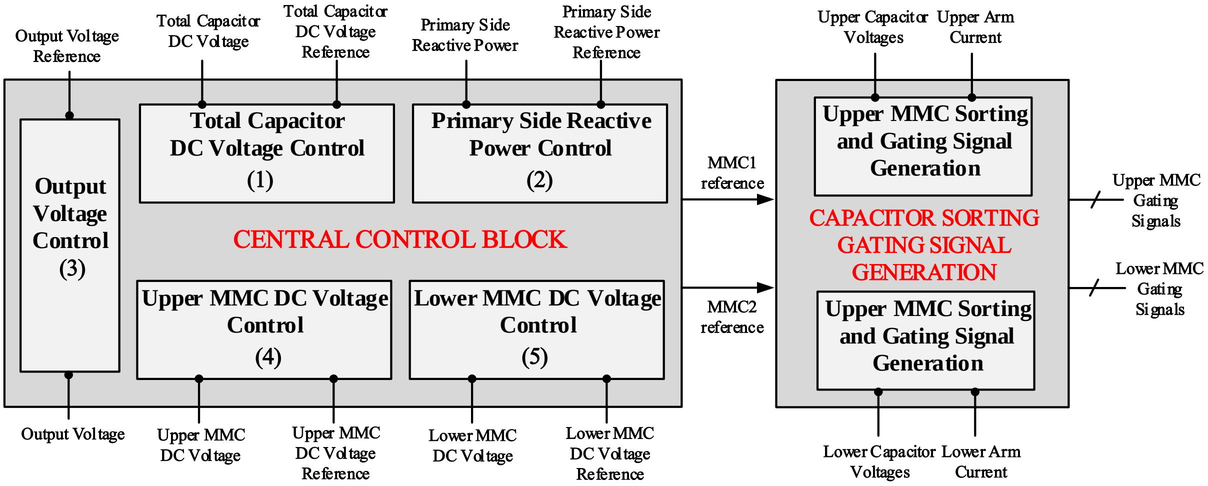


Figure 3. **SST control blocks, sorting and gating signal generation block**

The central control block monitors the instantaneous control variables and the reference values, then generates the reference of the two MMCs and sends them to the capacitor sorting and gating signal generation block. The "sorting" process is essential for charge equalization and keeping the voltage of all capacitors remains within reasonable and stable bounds. This bubble sorting block will perform the following operations: i) sort the capacitor voltages from min to max, ii) determine the number of capacitor that needs to be inserted or bypassed, iii) determine which capacitor needs to be charged or discharged to keep all capacitor voltages balanced, and iv) generate the switching signals for both MMCs.

Galvanic Isolation

Galvanic isolation is to protect human operators and low-voltage circuitry from high voltage. The capacitor allows only alternating current to flow but blocks direct current. The capacitor-type isolation is a circuit design technique that enables circuits to communicate and eliminates any unwanted direct current that flows between them. In the proposed SST, the upper series column of capacitors blocks any direct current flowing from the high voltage side.

4. CASE STUDY: SOLID STATE DISTRIBUTION TRANSFORMER

The foregoing SSDT was modeled in detail using an EMT simulator to assure operation in accordance with the principles. A 14.4 kV/347 V 167 kVA single-phase solid-state transformer case is studied. This is one phase of a 500 kVA, 25kV/600V pad mount distribution transformer. The Solid-State Distribution Transformer (SSDT) parameters are listed in Table 1.

Table 1 SSDT parameters

	Primary Side	Secondary Side
Voltage Rating	$14.4\ kV, RMS$	$0.347\ kV, RMS$
Fundamental Frequency	$60\ Hz$	$60\ Hz$
Resonant Tank, L	$0.0011165\ H$	$0.00005\ H$
Resonant Tank, C	$3\ \mu F$	$66.98\ \mu F$
Smooth inductor, L	$0.1\ H$	$0.005\ H$
Main Switch	Bi-directional RB-IGBT* $f_{sw} = 2200\ Hz$	Bi-directional RB-IGBT $f_{sw} = 2200\ Hz$
	Sub-Module parameters	
Sub-Module	A column of Full-Bridge Submodules	
Upper MMC	Level: 20	$C_{SM}{}^{**} = 8000\mu F$ $V_{MMC2} = 17.86kV$
Lower MMC	Level: 20	$C_{SM} = 30000\mu F$ $V_{MMC2} = 2.5kV$

* RB-IGBT (Reverse Blocking IGBT) enables bi-directional switching capability without additional anti-parallel diode [8].

** $C_{SM}$is the Sub-module capacitance, V_{MMC1} is the total capacitor voltage of the upper MMC, V_{MMC2} is the total capacitor voltage of the lower MMC.

SSDT Operation under Different Load Conditions

The SSDT was simulated in two conditions: 1) passive loads and 2) an ideal voltage source to model the conditions that will most probably appear in a distribution network.

1) **Passive Load:** RLC loads were connected to the secondary side to confirm the transformer's ability to work with linear and non-linear loads. The amount of power delivered to the secondary side is dependent on the load impedance. The experiment results in Fig. 4 and 5 are performed with passive loads. In Fig. 4, while we applied step changes to the load impedance, the output current and power changed correspondingly. The input and output voltages were maintained at a constant level as expected.

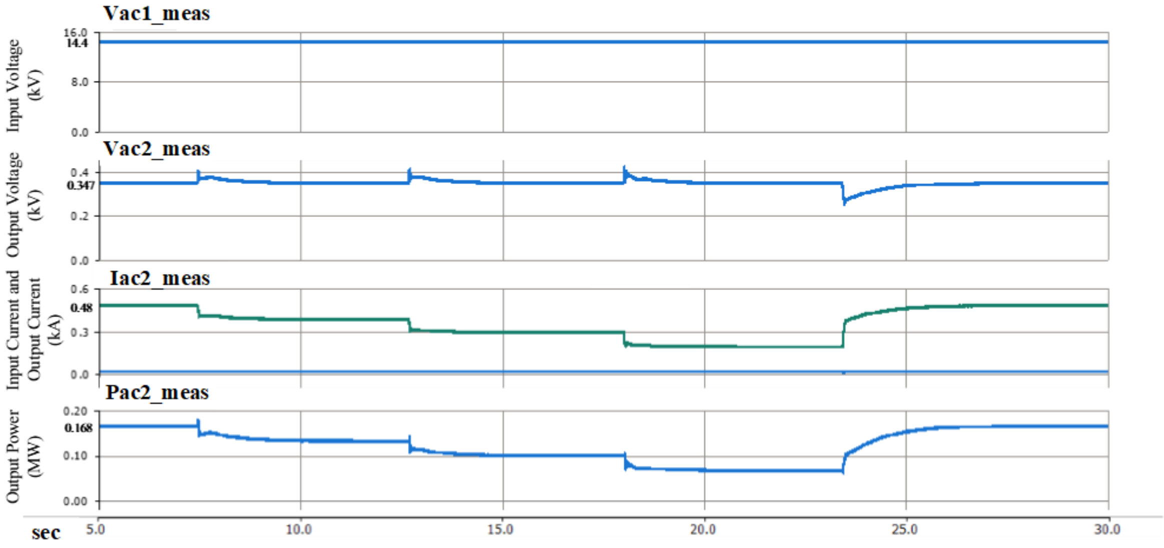


Figure 4. Input voltage (V_{ac1_meas}) and output voltage (V_{ac2_meas}) RMS, input current (I_{ac1_meas}) and output current (I_{ac2_meas}) RMS, and output power (P_{ac2_meas})

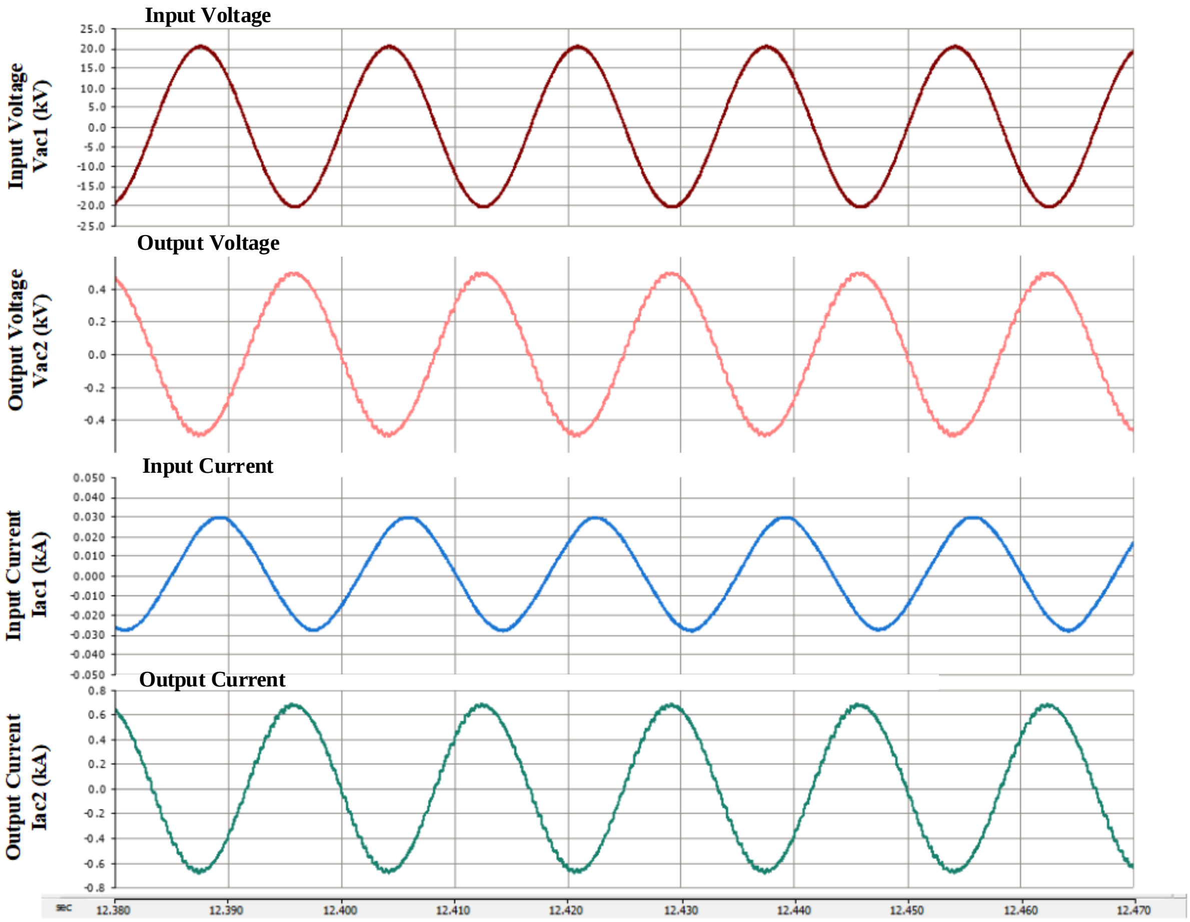


Figure 5. **Waveforms of instantaneous voltages and currents (Input Voltage: V_{ac1}, Output Voltage: V_{ac2}, Input Current: I_{ac1}, and Output Current: I_{ac2})**

Fig. 5 shows the instantaneous voltage and current waveform of the following signals: i) Input Voltage, ii) Output Voltage, iii) Input Current, and iv) Output Current. The experiment was simulated with an RLC load.

Since the SSDT operates at 2.2 kHz, it is important to reduce the harmonic emissions introduced by the power electronics device. We implemented smoothing inductors on both sides of the transformer to eliminate the harmonics. The harmonic emission assessment is conducted based on the requirements in IEEE std. 519 [9]. The total harmonic distortion (THD) of the voltages and currents were measured and listed in Table 2. All THD measurements satisfy the IEEE std. 519 requirements.

Table 2 ***THD measurements of SSDT's input voltage, output voltage, input current, and output current***

	Input Voltage V_{ac1}	**Output Voltage V_{ac2}**	**Input Current I_{ac1}**	**Output Current I_{ac2}**
THD (%)	**0.7%**	**2.1%**	**2.0%**	**2.1%**

2) **Ideal Voltage Source**: the transformer was then connected to an ideal voltage source to test the ability to provide bi-directional power flow by shifting the phase angle. In the case of having distribution energy resources on the secondary side, the SSDT should be able to deliver power backward. Fig. 6 shows an example of the SSDT delivering 0.05 MW from the primary side to the secondary side (0s~20s), and then the power flow direction changed at 20 seconds, the same amount of power flowed from the low voltage side to the high voltage side.

   Fig. 7 shows the accomplishment of primary side reactive power control.

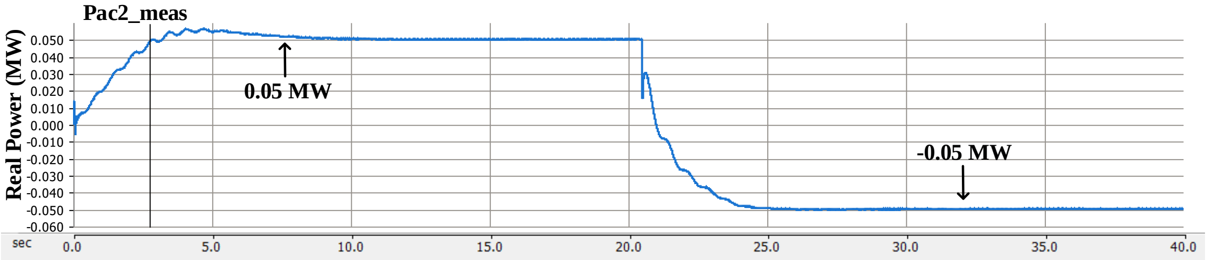


Figure 6. Real power waveform of sending power backward

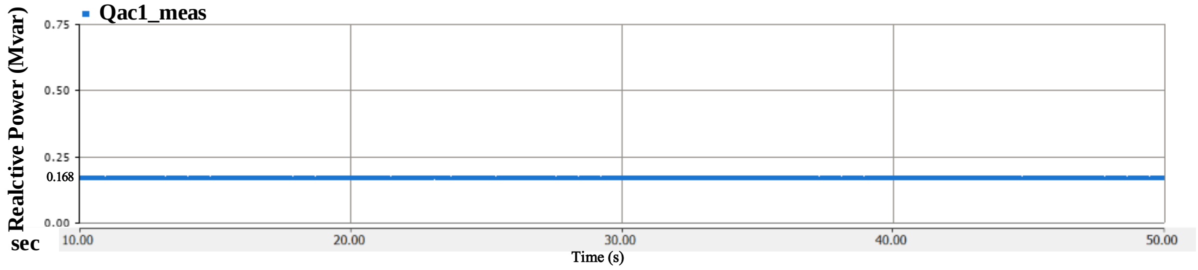


Figure 7. Reactive power waveform of sending power backward

SSDT MMC DC Voltage Control

Fig. 8 shows the total capacitor column DC voltage: VcT (blue), the upper MMC DC voltage: VcT_1 (green), and the lower MMC DC voltage: VcT_2 (red). Three separate controls keep the capacitor column voltage at 20.36 kV, the upper MMC voltage at 17.86 kV, and the lower MMC voltage at 2.5 kV.

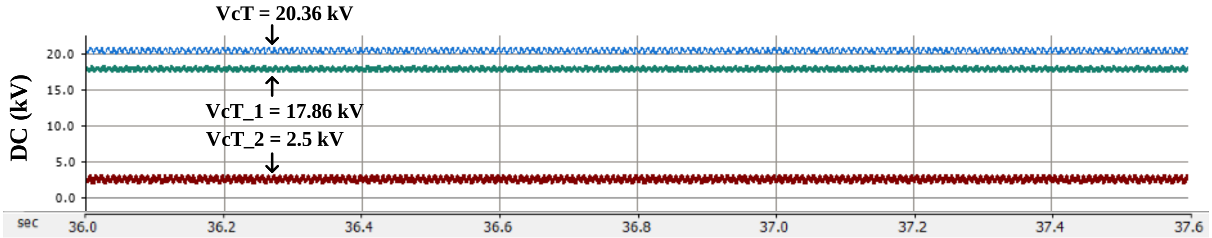


Figure 8. Total capacitor column DC voltage ($V_C T$), MMC1 capacitor DC voltage ($V_C T\_1$), MMC2 capacitor DC voltage ($V_C T\_2$)

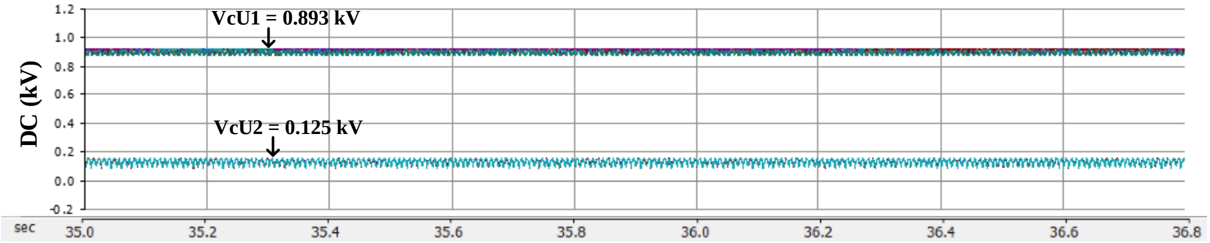


Figure 9. Individual capacitor voltages of upper MMC ($V_C U1$) and lower MMC ($V_C U2$)

Fig. 9 is the individual capacitor voltages of upper MMC and lower MMC. On the top, $V_C U1$ is the array of capacitor voltage in the upper MMC, and the bottom signals $V_C U2$ is the array of capacitor voltage in the lower MMC. The bubble sorting technique successfully maintains each capacitor voltage $V_C = \frac{V_C T}{\#\ of\ capacitors}$, which is balanced and equalized.

Fig. 10 shows the input resonant current Is1 and output resonant current Is2, by alternately receiving a current pulse from one end to another, the SSDT achieves power transformation. The current pulses are turning off at current zero, which is designed on purpose to make the switching frequency f_{sw} matches the resonant frequency f_r, so that zero-current switching (or soft-switching) can be achieved to minimize the switching losses.

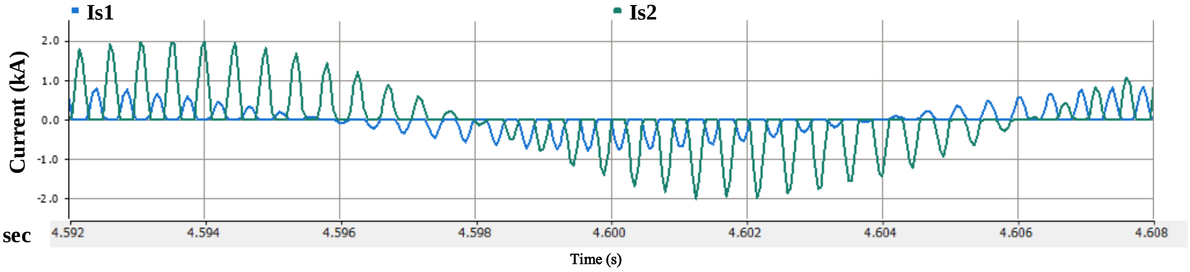


Figure 10. Input and output current pulses

SSDT Protection System and Fault Study

The protection system of the SSDT monitors the HV side and LV side currents, in case of a line to ground fault occurs, the system will immediately open the fault side main switch to prevent any overcurrent from damaging devices. The protection mechanism can be summarized as follows: when the fault occurs, the overcurrent detector senses the current higher than the selected current limit, it will immediately generate a command to permanently open the fault side switch. Even the fault is cleared, the switch will remain open until the overcurrent protection is manually turned off. In the simulation, two single-phase fault modules have been placed on each side of the transformer to imitate the appearance of a short circuit fault that will cause an overcurrent.

As an example to explain the protection system, a line-to-ground fault was applied to the secondary side of the SSDT at 20 seconds with a duration of 0.05 seconds, then the system was recovered at 30.05 seconds. In Fig. 11, the RMS output current waveform illustrates the current behavior during the fault. The overcurrent protection system detects the fault and forces the switch S2 to open. The switch will be forced to open at 1) overcurrent, 2) Is2 (the current going through S2) reaches 0. The latter criteria are to make sure the switch is not opened at peak of Is2 (for zero-current switching off).

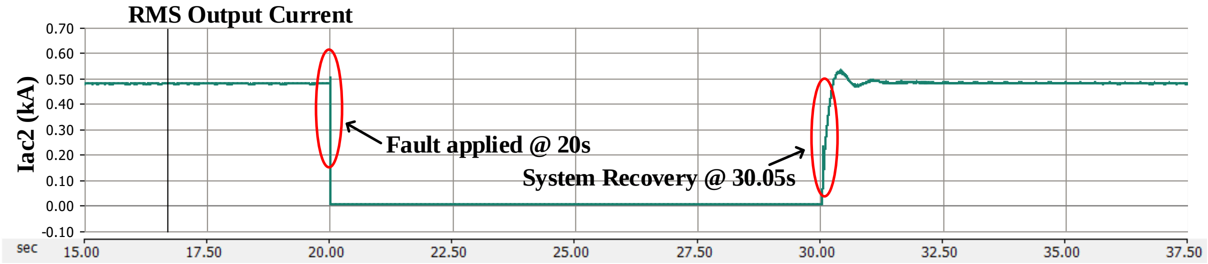


Figure 11. The RMS output current waveform during fault and recovery

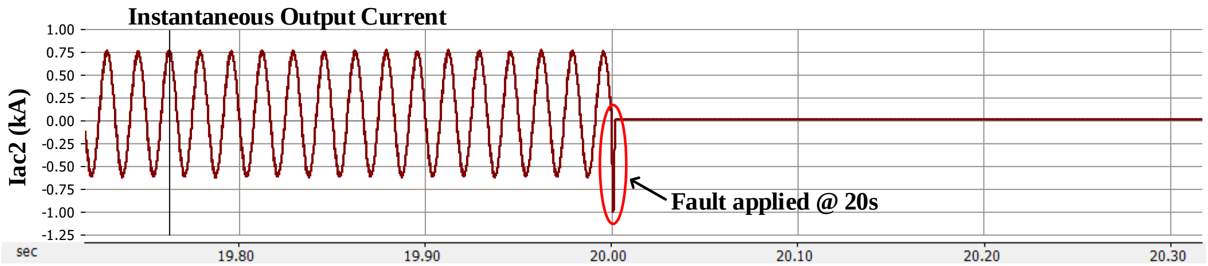


Figure 12. **The instantaneous output current (fault applied at 20 seconds)**

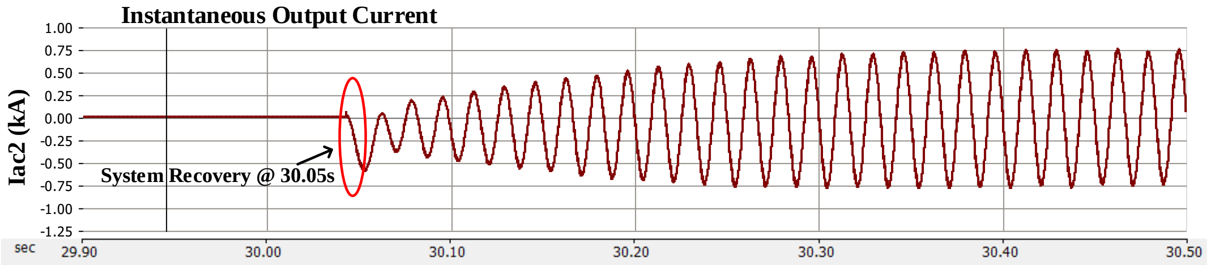


Figure 13. **The instantaneous output current (system recovery at 30.05 seconds)**

The instantaneous output current in Fig. 12 shows the details of fault was applied at 20 seconds. The protection system detected the current spike and immediately turned S2 off. The current went to zero, the fault was cleared and the user will manually restart the system.

Fig. 13 shows the instantaneous output current smoothly recovered after restarting at 30.05 seconds. Overall, in case of fault, the system will open the fault side switch immediately to isolate the SSDT from over-current damage. When the fault is cleared, the user can manually set a restart order, and the SSDT will go back into operation.

5. FEATURES OF THE PROPOSED SSDT

The solid-state distribution transformer offers more features than the conventional transformer and other SSTs:

- Physical size reduction for the same power rating helped by high-frequency internal operation.
- The SSDT is the hub of future electrical systems, it does not only perform energy conversion but with smart control that enables more efficient energy transmission between the grids.
- Reactive power compensation.
- No losses are caused by the eddy current generated by the harmonics of non-linear loads.
- More environment friendly, and easier maintenance.
- It is a pure solid-state transformer that has no magnetically-based transformer involved and therefore does not generate magnetostriction noise thereby being environmentally friendly.
- Uses much fewer solid-state stages compared to other SSTs, with simpler control as it does not need a power order.
- The solid-state switches will provide immediate protection against internal or external faults as well as effective short circuit capacity within the maximum current rating of the solid-state components.
- The repair will usually be just the replacement of small components and done quickly.
- It is lightweight without an iron core and oil and will be easier to transport.
- It will be less prone to fire and explosion due to no bulk oil.

6. CONCLUSION AND FUTURE WORK

With more renewable energy resources involved, the modern power system is changing, and the trend of transforming to a smart grid for system resilience is on the way. SST is a novel and important development that will be a game-changer and eventually replace the conventional transformers. After decades of research and development in universities and research institutes, the technology is more and more mature which attracts industry attention. The proposed solid-state distribution transformer has demonstrated the ability to become a hub in the future grid that provides more efficient communication among the smart electric network.

The proposed SSDT is based on the principle of capacitor-based power transformation. It uses a single-stage power converter. It transforms power directly from AC to AC without the use of a dual active bridge (DAB) converter. The simulation shows that the SSDT can successfully serve as a single-phase 167 kVA pad-mounted distribution transformer, with a typical single-phase voltage ratio of 14.4 kV: 347 V. The transformer can provide features such as soft-switching, bi-directional power flow, control of the primary side reactive power, and high efficiency. Many applications beyond the padmount distribution transformer are presented herein.

Overall, the results are stable when the SSDT is connected to 1) RLC load, 2) voltage source, 3) a combination of passive elements and voltage source. When an energy source is on the secondary side, the SSDT can send full power backwards by shifting the phase angle (full power is 0.167 MW). The simulation efficiency was calculated by measuring the instantaneous input and output power on each end of the SSDT, the calculated efficiency can reach 98% and will require cooling typical for solid-state facilities. However, the efficiency evaluation may be limited in EMT simulation, which uses ideal components that could lead to high efficiency. The actual efficiency of the physical device needs to be determined with a prototype. The prototype of the proposed SSDT is the next stage of the project. The prototype building procedure will include but is not limited to 1) Power Hardware-in-the-loop (PHIL) simulation to test the physical device, 2) Controller Hardware-in-the-loop (CHIL) simulation to implement the controller, 3) interface of the device with the controller. All of the above work will be performed with a real-time simulator.

*The proposed work is a part of the patent-pending “Step-Wise Power Transformation” [6].

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