

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Digital Object Identifier (DOI): 10.1109/ECCE.2016.7855451

IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, USA, 2016

**Smart transformer-based hybrid grid loads support in partial disconnection of MV/HV power system**

Chandan Kumar

Zhi-Xiang Zou

Marco Liserre

### **Suggested Citation**

C. Kumar, Z. Zou and M. Liserre, "Smart transformer-based hybrid grid loads support in partial disconnection of MV/HV power system," IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-8.

# Smart Transformer-Based Hybrid Grid Loads Support in Partial Disconnection of MV/HV Power System

Chandan Kumar, *Member, IEEE*

Department of Electronics and Electrical Engineering  
Indian Institute of Technology Guwahati, India  
chandank@iitg.ernet.in

Zhixiang Zou\*, *Member, IEEE*

Marco Liserre\*\*, *Fellow, IEEE*

Chair of Power Electronics, Faculty of Engineering  
Christian-Albrechts-University of Kiel, Germany  
\*zz@tf.uni-kiel.de, \*\*ml@tf.uni-kiel.de

**Abstract**—Double circuit lines are common for transmitting the electrical power in high voltage (HV) and/or medium voltage (MV) power system. During the faults in one of the lines or transformers of the double circuit lines, one line is disconnected from the system and the healthy line is utilized for supplying the entire load. In that case, the transformer supplying the entire load could be overloaded. For the safe operation of the transformer, it is needed to disconnect some of the loads. This partial disconnection of MV/HV power system can severally effect the performance of critical loads. Recently, power electronic based transformer equipped with effective control and communication called smart transformer (ST) has been proposed for installation in the distribution system in place of conventional transformer. One of the most important feature of ST is to allow for connection of ac and dc grid forming hybrid grid which allow easy integration of renewable energy sources and storage. Considering these feature of ST, this paper proposes a new functionality of the ST where it provides continuous power to a section of the loads during the partial disconnection of MV/HV power system and improves the performance of power system. This new feature of ST has been proved through power system computer aided design (PSCAD) software based simulation results. Power hardware in loop (PHIL) and control hardware in loop (CHIL) is under development to test the idea.

**Index Terms**—Smart transformer (ST), power distribution system, renewable energy.

## I. INTRODUCTION

Advancement in the power semiconductor technology has made possible to propose several power electronics devices for improving the performance of power transmission and distribution system. Power electronics based custom power devices (CPDs) namely distribution static compensator (DSTATCOM), dynamic voltage restorer (DVR) and unified power quality conditioner (UPQC) are major devices used for improving the power quality issues and grid stabilization [1]. Further, with the increase in the electrical power generation through the renewable, more and more grid connected inverters are employed in the power system [2]. These inverters transfer available power at the dc bus into the grid, additionally, provide advanced operational features like dynamic control of real and reactive power, standby operation within a range

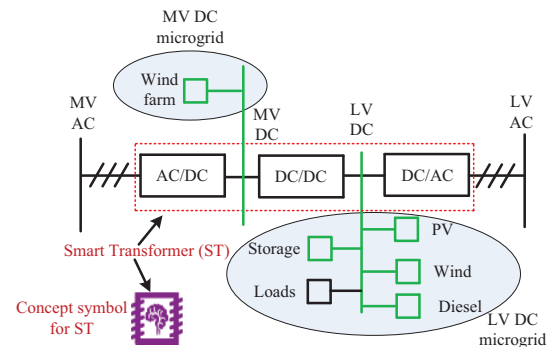


Fig. 1. A schematic of ST in a hybrid power distribution system.

of voltage/frequency and fault ride through during voltage disturbances.

In the recent time, one of the most enabling power electronics technology which has found its application in the distribution system is smart transformer (ST) [3]–[9]. The ST, proposed as an alternate for conventional power transformers (CPTs), is a power electronics transformer equipped with control and communications offers specific services to the grid. In addition to features like voltage transformation and isolation between the medium voltage (MV) and low voltage (LV) sides similar to CPTs, the ST provides sinusoidal voltage in LV distribution system and balanced sinusoidal unity power factor current in the MV grid side. In addition to these operational features, the ST allows connection of ac and dc grid forming hybrid grid which facilitates easy integration of renewable energy sources and storage [10]–[15]. A typical ST operated in the hybrid power distribution system is shown in Fig. 1.

Few applications of ST for improving performance of MV power system are presented in the literature. In [16], authors have proposed an ST for providing load compensation features in MV power system. In [15], a dual microgrid based ST is proposed to support the loads of other feeders when MV grid is not present. A voltage/reactive power control scheme is presented in [17], [18] to minimize the losses in the line and keep the voltages at the feeder within the limits. Since the application of ST in power system is still new and

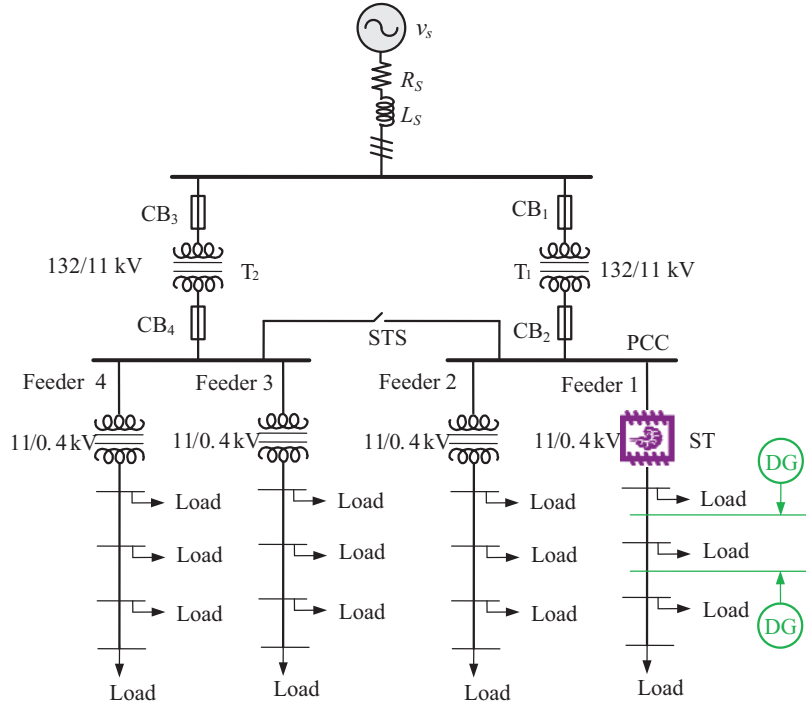


Fig. 2. Single line diagram of envisioned power distribution system with conventional power transformer is replaced by a smart transformer in feeder 1.

its operational features in MV power system are not fully explored, new operational features of ST need to be further investigated for making its application feasible.

This paper proposes a new feature of ST in MV power system. In a double circuit power system, there is always possibility of the partial disconnection of MV/HV power lines either due to scheduled maintenance or due to faults. In this case, all the loads are supplied through the reduced number of transformers resulting in the overloading of transformer or disconnection of some loads. However, neither of the scenario can be appreciated. Taking advantages of flexibility in operation, communications, bidirectional power transfer capability, and distributed energy resources (DERs) and energy storage systems (ESSs) at the dc link, this paper proposes a new feature of the ST during the partial disconnection of the MV/HV power system. In the proposed feature, the ST provides continuous power to a section of the power system and improves the performance of loads connected to other feeders as well as improves the performance of the power transformer. These additional features improve the utilization of ST as well.

The paper is organized as follows. The Section II provides detailed description of the system configuration. Section III explains the circuit diagram of the ST. Control and operation of ST in the proposed scheme is explained in Section IV. Simulation results are given in Section V. Section VI provides explanation of RTDS structure. Conclusions are given in Section VII.

## II. DESCRIPTION OF THE SYSTEM CONFIGURATION

Fig. 2 shows single line diagram of envisioned power distribution system with conventional power transformer is

replaced by a smart transformer in feeder 1. The MV line and grid is simplified by Thevenin's equivalent of voltage  $v_s$  and impedance  $R_s + jX_s$ . The network consists of two HV/MV power transformers T1 and T2 with a rating of 1.2 MVA, 132/11 kV. Each power transformer supply several loads connected to the LV side of 400 V through the distribution transformers of rating 11/0.4 kV. A static transfer switch (STS) is utilized to continuously supply power to entire system during disturbances. For simplicity in the presented case, it is assumed that each transformer T1 and T2 supplies the two different feeders independently. Various types of loads are connected to all the four feeders, and few of them are critical loads which require continuous power supply for satisfactory operation. In the feeder 1, the distribution transformer is replaced by a smart transformer. For increasing the hosting capacity of the ST based system, a variety of DERs such as PV, wind turbine, diesel generator and ESSs are connected to the electric interfaces provided by the ST.

Two operational scenarios are presented in this paper. In normal operation, the STS is off and the power transformers T1 and T2 operate in a paralleled way independently. All the loads of system are supplied by the utility and available DGs together. Moreover, the ST draws/supplies balanced sinusoidal current from the grid irrespective of the load conditions at its low voltage side. When the CB3 and CB4 are opened due to grid anomaly, the STS is turned on and thus transformer T1 has to supply the loads of all the four feeders. In this scenario, there is possibility that the transformer T1 may get overloaded and the utility may force consumers to switch off some of the loads. In that scenario, it is proposed in this work that the ST will inject active power into the medium voltage side in such a way that the loads connected at the feeder 2

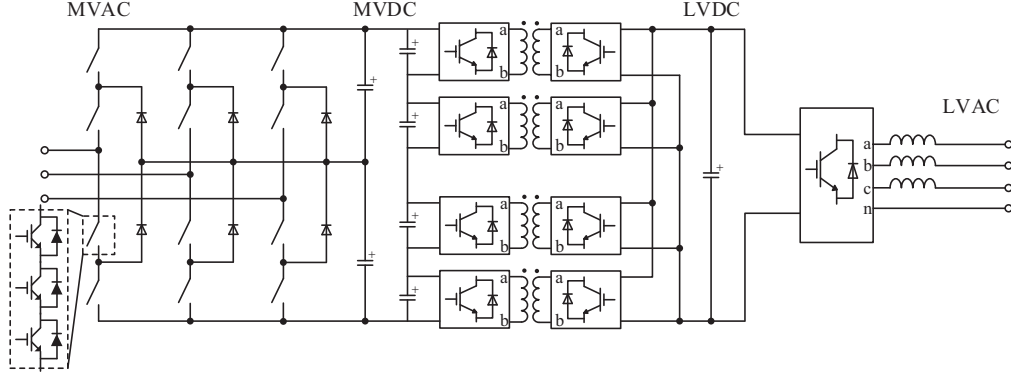


Fig. 3. Three stage smart transformer with two intermediate DC-links.

are operating satisfactorily while drawing allowable amount of power from the utility grid. Therefore, the ST will supply loads of feeder 1 and additionally inject power into the grid to support the loads of feeder 2. Moreover, the transformer T1 will continue transferring active power based on its power rating and load requirements. In this work, it is considered that the transformer T1 will completely supply for the feeders 3 and 4 during disconnection of the transformer T1. In this way, the power transfer through T1 could be largely reduced and therefore the overloading problem can be alleviated by means of ST.

The voltages at the point of common coupling (PCC) are represented by  $v_{ta}$ ,  $v_{tb}$ , and  $v_{tc}$  for phases  $a$ ,  $b$ , and  $c$ , respectively. The currents  $i_{l1a}$ ,  $i_{l1b}$ ,  $i_{l1c}$  and  $i_{l2a}$ ,  $i_{l2b}$ ,  $i_{l2c}$  are currents flowing through the MV side feeder 1 (MV side ST current) and feeder 2, respectively.

### III. CIRCUIT DIAGRAM OF SMART TRANSFORMER

In this paper, a three stage smart transformer with two intermediate dc-link is employed and shown in Fig. 3. In the MV side, a neutral point clamped (NPC) multilevel converter is chosen to implement the ac/dc conversion. Several modular dual active bridge (DAB) converters are used as dc/dc converters. In the low voltage side, the interleaved full bridge converters are selected to convert the low voltage dc-link voltage to low voltage ac voltage. Since the key purpose of this work is to improve the performance of MV side, we will mainly focus on the MV side operation scenarios and rating as well as component design aspects in the following part.

In order to withstand the 11 kV voltage of MV side, proper number of IGBTs and fly-wheel diodes must be embedded in each arm of the NPC converter. In this work, three 4.5 kV IGBTs are connected in series for each switch of the NPC as shown in the dash rectangle of Fig. 3. Meanwhile, the nominal current of IGBTs is strongly dependent on the rated power of the NPC converter. The sizing of the NPC converter should be properly designed according to the services provided by the two possible operation scenario mentioned in Section II. In normal operation, the ST supplies power to the loads

connected to its low voltage side and at the same time, offers compensation features to compensate reactive and harmonic components of currents of feeder 2. At this regard, the transfer active power and the compensated reactive as well as distorted power must be considered in the NPC converter sizing design. During partial disconnection of MV/HV power system, the ST must partly cover the power of critical loads of other feeders and make sure the power transfer through the main transformer (for example, T1 in this work) within the security limits. Therefore, the maximum power injection must be considered and beneath the security rating limit of the semiconductors. In general, the sizing of the NPC converter would depend on the maximum transferred active power during HV/MV anomaly and compensated reactive as well as distorted power during normal situation.

### IV. CONTROL AND OPERATION OF THE ST IN THE PROPOSED OPERATION

This work uses a three stage smart transformer with two intermediate dc links. The ST has two modes of operation, during normal circuit conditions and during the partial disconnection of the MV/HV power system. The MV ac-dc rectifier operates in current control mode throughout the operation and supplies/absorbs power based upon the requirements. The dc-dc converter maintains a constant voltage at the LV dc link. The dc-dc converter continues to operate similarly with the possibility of reversal in power flow during the fault conditions. The low voltage dc-ac inverter maintains a constant sinusoidal voltage at the load terminal. The details are presented in this section.

#### A. Normal Operation of the ST

1) *Operation of the Rectifier:* In normal operating conditions when the each HV/MV transformer supplies power to its allocated loads, the ST provides power to loads connected to its low voltage side and/or injects remaining power into the MV grid depending upon the available DER and load demand. Also, the ST provides load compensation features

to compensate reactive and harmonic components of currents of feeder 2. To compute the reference MV grid currents that must be supplied/absorbed by the MV rectifier, instantaneous symmetrical component theory based reference generation scheme is used [19]. The reference rectifier currents which take care of real power exchange between the ST and MV grid are computed as follows [19]:

$$\begin{aligned} i_{gra}^* &= \frac{v_{ta1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{loss} - P_{res}) \\ i_{grb}^* &= \frac{v_{tb1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{loss} - P_{res}) \\ i_{grc}^* &= \frac{v_{tc1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{loss} - P_{res}). \end{aligned} \quad (1)$$

In (1), the terms  $v_{ta1}^+$ ,  $v_{tb1}^+$ , and  $v_{tc1}^+$  are fundamental positive sequence voltages at PCC in three phases in Fig. 2. The fundamental positive sequence of phase-a PCC voltage is set as reference waveform. For determining the frequency and angle reference of the PCC voltage, a phase locked loop (PLL) is used. The power  $P_{load1}$  is the average load power demand of loads connected to the LV side of ST (i.e., at the feeder 1), whereas  $P_{res}$  is power from renewable energy resources available at the dc bus of the ST. The term  $P_{loss}$  includes losses in the MV rectifier. The power loss  $P_{loss}$  is computed using a proportional integral (PI) controller as follows:

$$P_{loss} = K_p e_{vdc} + K_i \int e_{vdc} dt \quad (2)$$

where  $K_p$ ,  $K_i$ , and  $e_{vdc} = 2V_{dcrefm} - (v_{dcm1} + v_{dcm2})$  are proportional gain, integral gain, and voltage error of the PI controller, respectively. The term  $P_{loss}$  helps in maintaining the MV dc link voltage at a reference voltage.

Further, the MV rectifier is also used to compensate for the unbalance and nonlinear current components of the loads connected to the feeders 2. This makes the total grid current at the MV side sinusoidal balanced and MV grid with transformer T1 sees only a balanced resistive loads at the PCC. The reference currents, which is called reference filter current here, that need to be supplied by the ST in the MV side to achieve these advantages are as follows:

$$\begin{aligned} i_{gfa}^* &= i_{l2a} - \frac{v_{ta1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2}) \\ i_{gfb}^* &= i_{l2b} - \frac{v_{tb1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2}). \\ i_{gfc}^* &= i_{l2c} - \frac{v_{tc1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2}) \end{aligned} \quad (3)$$

In above equation, the currents  $i_{gfa}^*$ ,  $i_{gfb}^*$ ,  $i_{gfc}^*$  and  $i_{l2a}$ ,  $i_{l2b}$ ,  $i_{l2c}$  are reference filter current and feeder 2 current, respectively in the phases  $a, b, c$ , respectively. The power  $P_{load2}$  represents average load powers in feeder 2.

The rectifier can provide load compensation in the considered system with an effective control in additional to supplying power to loads connected to feeder 1. Therefore, the total reference currents of the rectifier circuit ( $i_{rec1-a}^*$ ,  $i_{rec1-b}^*$ , and

$i_{rec1-c}^*$ ) are given as are given as

$$\begin{aligned} i_{rec1-a}^* &= -i_{gra}^* + k_1 i_{gfa}^* \\ i_{rec1-b}^* &= -i_{grb}^* + k_1 i_{gfb}^* \\ i_{rec1-c}^* &= -i_{grc}^* + k_1 i_{gfc}^* \end{aligned} \quad (4)$$

In the above equation, the term  $k_1$  can have a value of either 1 or 0. The value 1 is selected when the control for load compensation of feeder 2 is activated, otherwise it will be set to 0. Therefore, depending upon the operating conditions of the power distribution system, the reference currents for rectifier circuit are selected.

2) *Operation of the dc-dc Converter:* In this work, the dc-dc converter is operated in such a way that it maintains LV dc link voltage at the constant reference voltage and maintains power flow between the MV and LV dc links. Here, a closed loop control of dc-dc converter is achieved with an outer LV dc bus voltage control loop and inner current control loop [7].

3) *Operation of the Inverter:* The dc-ac inverter maintains a balanced sinusoidal voltage with a constant frequency at the LV distribution system throughout the operation. For simplicity of the operation, the reference sinusoidal voltage is computed based on the phase locked loop (PLL) used for the MV rectifier circuit. The reference LV terminal voltage of the inverter is maintained at a constant value of 230 V rms per phase [7].

#### B. Operation of ST During Partial Disconnection of MV/HV Power System

Partial disconnection of the considered power system is experienced when the HV/MV power transformer T2 is disconnected from the service. It can happen either due to the fault in the transformer T2 or in the line itself or due to the scheduled maintenance of transformer T2. In this case, the switch STS is turned on and the entire load of transformer T2 is transferred to the transformer T1. In the situation when the transformer T1 is supplying all loads, it could be overloaded easily. In that case, the utility expects that the customers must switch off some loads from the circuit to prevent overloading condition of transformer T1. This can lead to the switching off of critical loads as well. Moreover, the energy storage system available at the dc link of the ST is activated in this period to support the entire load of feeder 1 as well as a portion of the loads of the feeder 2 depending upon the storage capacity and the ST power rating availability. In this case, the operation of the different devices are given as follows.

1) *Operation of the Rectifier:* Since the powers  $P_{load1}$  and  $P_{load2}$  are power requirements of the feeder 1 and feeder 2, respectively, the total power requirement of combined load of feeder 1 and feeder 2, is  $P_{load1} + P_{load2}$ . Let the storage and DER available at the ST is  $P_{st}$ . Out of the total power rating of 1.2 MW of transformer T1, let the power  $P_0$  is set for the feeder 1 and feeder 2 whereas the remaining power rating is utilized to support the critical loads of the feeders 3 and feeder 4. Also, it is assumed that the power  $P_0$  is lower than the total power requirement of feeder 2. The rectifier supplies this deficit of power and keeps the operation of the loads of feeder 2 continuous. The reference rectifier currents

TABLE I  
SIMULATION PARAMETERS

System quantities	Values
Source rms voltage	11 kV line-line, 50 Hz
Source impedance	$Z_s = 0.1 + j 3.14 \Omega$
Feeder 1 loads	Unbalanced nonlinear load
Feeder 2 loads	Unbalanced nonlinear load
Nonlinear loads	Diode bridge rectifier loads
Linear loads	single and three phase RL loads
Rectifier parameters	DC link voltage, $V_{dcm} = 15$ kV, Filter inductance, $L_{fh} = 100$ mH, Filter resistance, $R_{fh} = 1 \Omega$ DC capacitance, $C_{dch} = 4000 \mu\text{F}$
VSI parameters	DC link voltage, $V_{dcl} = 600$ V, Filter inductance, $L_{fl} = 5$ mH, DC capacitance, $C_{dcl} = 2000 \mu\text{F}$ , Filter parameters, $C_{shl} = 20 \mu\text{F}$

in this case supplying for this partial power requirement be  $i_{gpa}^*$ ,  $i_{gpb}^*$ , and  $i_{gpc}^*$  for three phases. The currents are given as follows:

$$\begin{aligned}
 i_{gpa}^* &= \frac{v_{ta1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{load2} - P_0 - P_{st}) \\
 i_{gpb}^* &= \frac{v_{tb1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{load2} - P_0 - P_{st}) \\
 i_{gpc}^* &= \frac{v_{tc1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load1} + P_{load2} - P_0 - P_{st}).
 \end{aligned} \quad (5)$$

As already mentioned, in addition to supplying the real power requirements, the ST still provides load compensation features. This feature is highly important during the situations when the power transformer is overloaded as it can reduce burden on the transformer T1 which can be effectively used for the transfer of increased real power from transformer. Therefore, the total reference currents of the rectifier circuit ( $i_{rec2-a}^*$ ,  $i_{rec2-b}^*$ , and  $i_{rec2-c}^*$ ) are given as following:

$$\begin{aligned}
 i_{rec2-a}^* &= -i_{gpa}^* + k_2 i_{gfa}^* \\
 i_{rec2-b}^* &= -i_{gpb}^* + k_2 i_{gfb}^* \\
 i_{rec2-c}^* &= -i_{gpc}^* + k_2 i_{gfc}^*
 \end{aligned} \quad (6)$$

Moreover, the load compensation feature can be activated/deactivated depending upon the need by selecting the value  $k_2$  either 1 or 0 in the above expression.

2) *Operation of the dc-dc Converter and the Inverter:* During this operation of the ST, the inverter maintains a constant and balanced voltage at the LV terminals as that of the normal operating conditions. The dc-dc converter maintains a voltage at the LV dc link.

## V. SIMULATION RESULTS

Performance of the proposed scheme is evaluated using PSCAD simulation software. The MV grid voltage is taken as 11 kV line-line rms. The impedance of the grid is set to  $1 + j3.14 \Omega$ . Both the feeders 1 and 2 have unbalanced and nonlinear loads. The MV dc link and LV dc link voltages

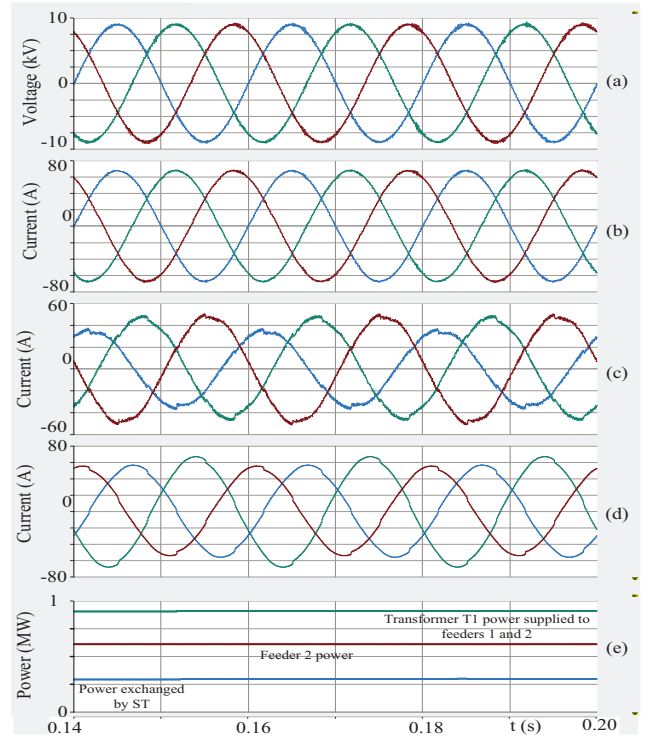


Fig. 4. Normal operation when STS is tuned off (T1 is supplying power to loads of feeder 1 and 2). (a) MV PCC voltages. (b) MV grid currents exchanged by feeder 1 and 2. (c) MV side ST currents. (d) MV side feeder 2 current. (e) Different active powers.

are maintained at the 15 kV and 600 V, respectively. The total active power requirements of feeders 1 and 2 is 300kW and 600 kW, respectively (total 900 kW). The performance is evaluated for following two operating conditions:

1. *Performance during Normal Operation:* The waveforms are shown in Fig. 4. In this case, it is shown that the active power requirements of feeders 1 and 2 are supplied by the transformer T1. Moreover, the reactive and harmonic power requirements of the feeder 2 are supplied by the ST. Hence, the current exchanged by the rectifier of the ST in the MV power system as shown in Fig. 4(c) contains real component needed to support loads of LV side of the ST and the unbalance reactive current component of the feeder 2. These currents are unbalanced and distorted. Consequently, the MV side grid voltage and total current supplied by the transformer T1 are balanced sinusoidal and in phase of each other. It reduces the current taken from the transformer T1 and improves its utilization (real power transfer capability). The total power requirement of the loads connected to the feeder 1 and feeder 2 are 300 kW and 600 kW, respectively. Therefore, the total power exchanged by the transformer T1 is 900 kW. These real powers are shown in Fig. 4(e). Moreover, the transformer T2 supplies loads connected to the feeders 3 and 4.

2. *Performance during Partial Disconnection of the HV/MV Power System:* In Fig. 5, it is shown that at the start of the simulation, the both transformers are operating independently and the transformer T1 is supplying loads of feeder 1 and feeder 2. The corresponding waveforms are shown in the figure. Due to a pre-scheduled maintenance work in the

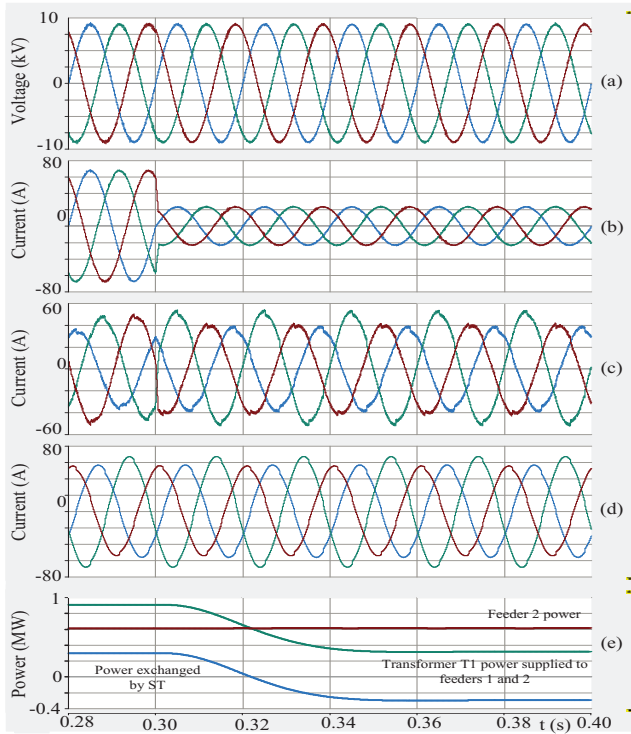


Fig. 5. Operation during partial disconnection of power system with STS is turned on (only T1 is supplying power to all the feeders). (a) MV PCC voltages. (b) MV grid currents exchanged by feeder 1 and 2. (c) MV side ST currents. (d) MV side feeder 2 current. (e) Different active powers.

transformer T2, it is disconnected from the service at the time  $t = 0.3$  s and the entire load is supplied by the transformer T1. In that situation, the transformer T1 cannot supply all the loads due to limitations of the current rating. For avoiding the situation of overloading, it fixes particular amount of power (volt ampere) for the particular section of the load. As can be seen from the Fig. 5, the transformer T1 sets a limit of power 300 kW for the combination of loads connected to feeder 1 and 2 from the total power capacity of the 1.2 MW (rest of the available power rating of T1 is utilized to support the loads of feeder 3 and feeder 4). However, the load requirement is 900 kW. In this situation, the ESS of the ST gets activated and supplies all the loads of the LV side of the ST and injects 300 kW power into the MV grid. This power supplied by the ST makes a power balance for the feeders 1 and 2 resulting in continuous operation of loads of feeder 1 and 2 without overloading the transformer T1. One important aspect of the ST operation is that it supplies reactive and harmonic components of feeder 2. Since, the unbalance and reactive current components of the feeder 2 are supplied by the ST, the feeder 2 exchanges only balanced and unity power factor current. Therefore, the transformer T1 is effectively utilized for the real power transfer.

## VI. ST RATING REQUIREMENTS

In the network considered in the Fig. 1, both the power transformers T1 and T2 are rated to 1.2 MVA. The all 11/0.4 kV distribution transformer as well ST supply to the maximum

load of 600 KVA. During normal operation the switch STS is off and each transformer T1 and T2 supplies to loads of its designated feeders. Also, in this operation scenario, the ST supplies for its LV side loads and also supplies into the MV grid depending upon the renewable energy sources at the LV DC links. Additionally, ST compensates for the load harmonic and unbalance of feeder 2. During the partial disconnection of MV/HV power system, the storage elements are brought into action to supply loads of the feeder 2.

The rectifier supplies real power into the grid depending upon the availability of the renewable sources and storage, and additionally also compensates for the reactive power requirements of the feeder 2 loads. Therefore, these two factors must be considered for designing of the rectifier circuit. In this paper, it is considered that entire loads of the feeder 2 will be supplied by the ST during partial disconnection of power system. The reason for this consideration is that the transformer T1 will have sufficient rating available to supply for loads of the feeder 3 and 4 (maximum power requirement of feeder 3 and feeder 4 is same as that of the power rating of transformer T1). The rating of the rectifier for this case is given as follows:

$$S_{rec} = \sqrt{3} \frac{V_{dcm}}{\sqrt{2}} I_{rec} \quad (7)$$

where the terms  $S_{rec}$  and  $I_{rec}$  are rectifier power rating and the rms current rating of the switch. Here, one aspect must be considered that the maximum loads on feeder 1 and feeder 2 are same which consequently requires a rectifier rating more than or equal to the rating of feeder 1 loads. Therefore, the rectifier rating is increased to cover the reactive and harmonic power requirement of the feeder 2. Moreover, the rectifier is not overrated for the reactive power support for the feeders 3 and 4 as these are not connected to the ST during normal operation.

Separating the rectifier power rating into the real and reactive power requirements, following relation is obtained

$$S_{rec} = \sqrt{Q_{2max}^2 + P_{2max}^2} \quad MVA. \quad (8)$$

where  $Q_{2max}$  and  $P_{2max}$  are maximum reactive and real power requirements of feeder 2, respectively. Since real power requirements are same at feeders 1 and 2,  $P_{2max} = P_{1max}$ . Hence, above equation reduces to,

$$S_{rec} = \sqrt{Q_{2max}^2 + P_{1max}^2} \quad MVA. \quad (9)$$

The above analysis shows that the advantages presented in this paper are achieved while considering the reactive power rating of feeder 2 alone, without increasing the real power rating of the rectifier circuit of the ST.

The dc-dc converter transfers power from the rectifier circuit to the inverter circuit and vice-versa. In the scenario when DERs are not present, entire power requirement of the ST loads will be supplied by the grid. Hence, the total power rating of dc-dc converter will be equal to the feeder 1 load rating. During partial disconnection of system, the maximum power that the dc-dc converter transfers is equal to the load power requirements of feeder 2. Since maximum power requirements

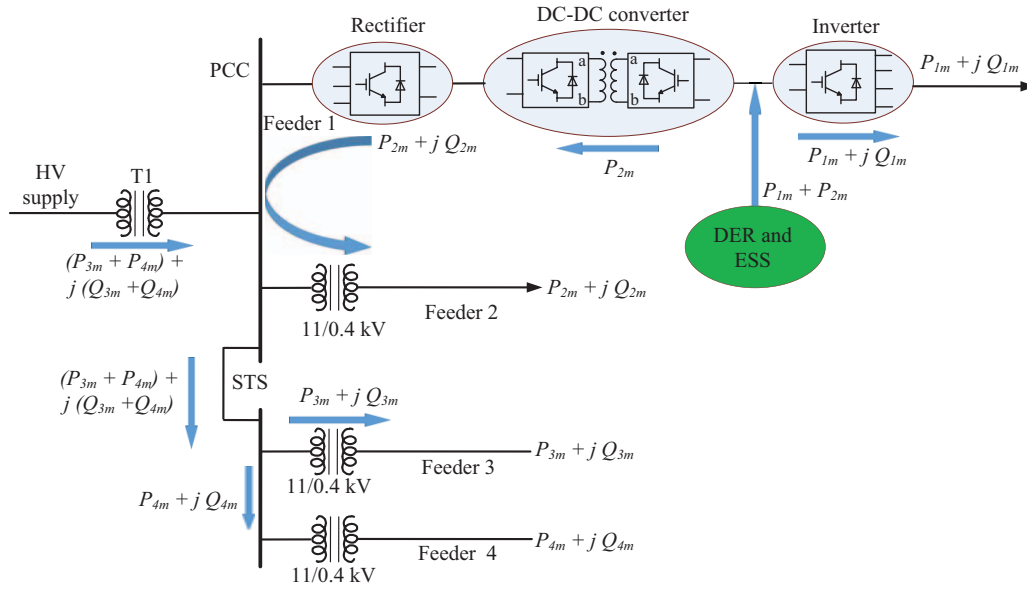


Fig. 6. Power flow diagram in the power system during partial disconnection of power system at the maximum load.

of feeder 1 and 2 are same, the dc-dc converter power rating remains unchanged.

The inverter provides a balanced voltage to the LV side loads of the feeder 1 and provides continuous power to the loads. Hence, the inverter rating must be same as that of the load real and reactive power rating.

The power flow diagram in the power system during partial disconnection of power system at the maximum load requirements are shown in Fig. 6. The feeder 2 loads are supplied by the ST utilizing DER and storage whereas the feeder 3 and 4 loads are supplied by grid through the transformer T1. In comparison to conventional ST based power system, only rectifier of ST is overrated to consider the reactive requirements of the feeder 2.

## VII. POWER HARDWARE IN LOOP (PHIL) AND CONTROL HARDWARE IN LOOP (CHIL) DESCRIPTION

The effectiveness of the scenario and the associated services can be verified in a real grid by means of PHIL or CHIL. The laboratory setup is shown in Fig. 7, where the ST and the grid can be simulated in the RTDS software and can be configured in the control desk via a computer. The control system of the ST is implemented in an external equipment (dSPACE 1006). The voltage and current of the grid are measured in the RTDS and sent to the ST control system.

There are two methods for the real-time simulation of a electric power system and its associated applications, which are power hardware in loop (PHIL) and control hardware in loop (CHIL), respectively. Depending on the methods, different laboratory configuration should be made. With CHIL, various components including power-electronics converters, relay protections, and machines can be tested in the software of RTDS. In this case, the LV side power converter of the ST can be configured in the RTDS and the voltage/current measurement (typically from 5 V to 10 V) can be directly sent from RTDS to the ST control system, which is the dSPACE.

The dSPACE generates the pulse signals and sends them back to RTDS in order to drive the power converter in the simulated grid of the RTDS.

On the other hand, for PHIL method, the experiments are carried out under certain power level. As a result, physical devices like power converters and relays as well as voltage/current sensors will be needed. In order to test these devices under a most realistic condition, the power amplifiers on the left side of Fig. 7 have to be included in the hardware loop. The measured voltage and current from RTDS will be amplified to the actual values of the grid (e.g. 0.4 KV for a LV grid) and sent to the dSPACE through voltage/current sensors as well as other power interfaces. In this case, the power converters that represent different ST stages can be controlled and subjected under an actual grid condition. The methodology and laboratory setup can be generalized for any ST-fed grid. Case studies including MV grid as well as associated services will be made in the future research.

## VIII. CONCLUSIONS

This paper has proposed a new operational feature of the ST operation. During normal operating conditions, the ST exchanges active power depending upon the load requirement and RES power availability and provides load compensation feature to eliminate need of power quality improvement devices at the feeder 2. During partial disconnection of the MV power system, the ST equipped with the ESS supplies active power into the grid to avoid overloading of the HV/MV transformer and allows loads connected to other feeder to operate satisfactorily. The ST also supplies reactive power requirement of other feeders which further avoids the overloading of the transformer. These operational features significantly improve the utilization of ST. The advantages are validated through extensive simulation results. A laboratory setup is being developed to study ST-fed grid including MV grid as well as associated services in the future research.



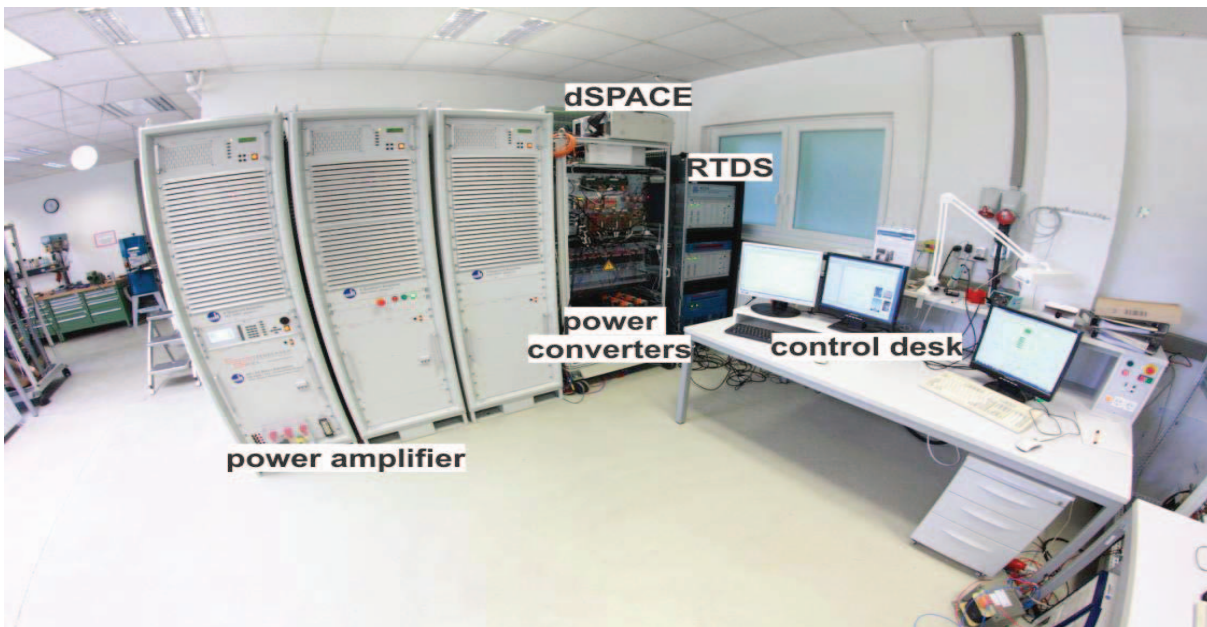


Fig. 7. Hardware in Loop (HIL) setup of smart transformer in distribution grid.

## IX. ACKNOWLEDGMENT

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement no. [616344].

## REFERENCES

- [1] M. H. Bollen, *Understanding power quality problems*. IEEE press New York, 2000, vol. 3.
- [2] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid converters for photovoltaic and wind power systems*. John Wiley & Sons, 2011, vol. 29.
- [3] M. Liserre, G. Buticchi, M. Andresen, G. D. Carne, L. F. Costa, and Z. X. Zou, "The smart transformer: Impact on the electric grid and technology challenges," *IEEE Ind. Electron. Mag.*, vol. 10, no. 2, pp. 46–58, Summer 2016.
- [4] Z. X. Zou, G. D. Carne, G. Buticchi, and M. Liserre, "Frequency adaptive control of a smart transformer-fed distribution grid," in *IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 3493–3499.
- [5] G. D. Carne, G. Buticchi, M. Liserre, C. Yoon, and F. Blaabjerg, "Voltage and current balancing in low and medium voltage grid by means of smart transformer," in *IEEE Power Energy Society General Meeting*, July 2015, pp. 1–5.
- [6] S. Bifaretti, P. Zanchetta, A. Watson, L. Tarisciotti, and J. 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.
- [7] G. De Carne, M. Liserre, K. Christakou, and M. Paolone, "Integrated voltage control and line congestion management in active distribution networks by means of smart transformers," in *IEEE 23rd International Symposium on Industrial Electronics (ISIE)*, June 2014, pp. 2613–2619.
- [8] X. She, A. Huang, and R. Burgos, "Review of solid-state transformer technologies and their application in power distribution systems," *IEEE Journal of Emerging and Selected Topics in Power Electron.*, vol. 1, no. 3, pp. 186–198, Sep. 2013.
- [9] R. Pena-Alzola, G. Gohil, L. Mathe, M. Liserre, and F. Blaabjerg, "Review of modular power converters solutions for smart transformer in distribution system," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2013, pp. 380–387.
- [10] A. Huang, M. Crow, G. Heydt, J. Zheng, and S. Dale, "The future renewable electric energy delivery and management (freedm) system: The energy internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133–148, Jan 2011.
- [11] Y. Jie, Z. Wu, and S. Bhattacharya, "Power dispatch strategy in microgrid integrated with solid state transformer," in *IEEE Power and Energy Society General Meeting (PES)*, July 2013, pp. 1–5.
- [12] S. Falcones, R. Ayyanar, and X. Mao, "A dc-dc multiport-converter-based solid-state transformer integrating distributed generation and storage," *IEEE Trans. Power Electron.*, vol. 28, no. 5, pp. 2192–2203, May 2013.
- [13] H. Krishnamoorthy, D. Rana, P. Garg, P. Enjeti, and I. Pitel, "Wind turbine generator-battery energy storage utility interface converter topology with medium-frequency transformer link," *IEEE Trans. Power Electron.*, vol. 29, no. 8, pp. 4146–4155, Aug 2014.
- [14] X. She, A. Q. Huang, S. Lukic, and M. E. Baran, "On integration of solid-state transformer with zonal dc microgrid," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 975–985, June 2012.
- [15] C. Kumar and M. Liserre, "A new prospective of smart transformer application: Dual microgrid (dmg) operation," in *41st Annual Conference of the IEEE Industrial Electronics Society, IECON*, Nov 2015, pp. 4482–4487.
- [16] —, "Operation and control of smart transformer for improving performance of medium voltage power distribution system," in *IEEE 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, June 2015, pp. 1–6.
- [17] Z. Shen, Z. Wang, and M. E. Baran, "Optimal volt/var control strategy for distribution system with multiple voltage regulating devices," in *Transmission and Distribution Conference and Exposition (TD)*, 2012 *IEEE PES*, May 2012, pp. 1–7.
- [18] D. Shah and M. L. Crow, "Online volt-var control for distribution systems with solid-state transformers," *IEEE Trans. Power Del.*, vol. 31, no. 1, pp. 343–350, Feb 2016.
- [19] A. Ghosh and G. F. Ledwich, *Power quality enhancement using custom power devices*. Kluwer academic publishers, 2002.