

© 2015 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/IECON.2015.7392798](https://doi.org/10.1109/IECON.2015.7392798)

41st Annual Conference of the IEEE Industrial Electronics Society, IECON 2015

A new prospective of smart transformer application: Dual microgrid (DMG) operation

Chandan Kumar

Marco Liserre

Suggested Citation

C. Kumar and M. Liserre, "A new prospective of smart transformer application: Dual microgrid (DMG) operation," *41st Annual Conference of the IEEE Industrial Electronics Society, IECON 2015 - Yokohama*, November 2015, pp. 004482-004487.

A New Prospective of Smart Transformer Application: Dual Microgrid (DMG) Operation

Chandan Kumar*, *Member, IEEE*, and Marco Liserre**, *Fellow, IEEE*

Chair of Power Electronics, Faculty of Engineering

Christian-Albrechts-University of Kiel, Germany

*chandan3107@gmail.com, **ml@tf.uni-kiel.de

Abstract—With the significant increase in renewable energy sources (RES) and storage elements, power distribution system needs new services for reliable and continuous operation. Smart transformer (ST) based on power electronics, control, and communication has been proposed for improving the performance of power system. However, operational capabilities and applications of ST with RES and energy storage in distribution system are still not explored in detail. In this paper, a new prospective of ST application, dual microgrid (DMG) operation, is proposed. In normal medium voltage (MV) grid operation, the ST supplies power to loads connected to its low voltage side and injects into the MV grid depending upon the available RES and load demand. During the voltage disturbances, the ST feeds power to the sensitive loads connected to the other feeders equipped with the conventional power transformers. In this case, the distribution loads are isolated from the MV utility grid. This ability of the smart transformer to isolate from the utility grid and provide continuous power to the sensitive loads of other feeders has potential to significantly improve the performance of power system as well as ST. With simulation results based on PSCAD/EMTDC software, this paper introduces for the first time an unexplored feature of the smart transformer.

Index Terms—Smart transformer (ST), dual microgrid (DMG), power distribution system.

I. INTRODUCTION

The structure of modern power distribution system has been changing tremendously with ever increasing connection of power electronics devices and distribution generators such as photovoltaic system, wind system, storage, etc. One of the most enabling technology which is expected to be integrated into the future distribution system is smart transformer (ST), which is a solid state transformer (SST) equipped with effective control and communication, at the place of conventional power transformer (CPT) [1]–[4].

A three-stage ST connects medium voltage (MV) power system to low voltage (LV) distribution system with intermediate dc links. In addition to providing features like voltage transformation and isolation between the MV and LV sides similar to CPTs, the ST has ability to provide additional features such as balanced sinusoidal voltage in LV distribution system, balanced sinusoidal unity power factor current in the MV grid side, no effect of MV side disturbances like sag, swell, transients etc., on the loads, availability of LV dc link for integration of distributed energy resources (DERs) and storage, etc. [4]–[8].

In ST applications, integration of distributed generation and storage to the low voltage dc link is one of the key

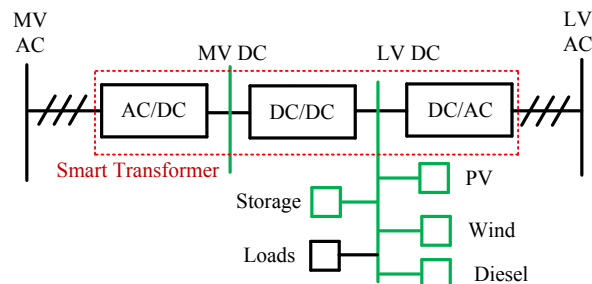


Fig. 1. A schematic of ST in distribution system for microgrid operation.

requirements [9]–[13]. In this scenario, a microgrid operation of the ST has been reported. A typical microgrid operation of ST is shown in Fig. 1. In this operation, the ST is connected to the MV system during normal operation and supplies power to the loads connected to its low voltage side or inject into the MV grid depending upon the available RES and load demand. During the voltage disturbances due to either fault in the MV network or intentional disconnection from the MV grid for maintenance purpose, the ST is disconnected from the MV supply and it feeds power to the loads connected to the low voltage side. Moreover, proper communication network necessarily be integrated into the ST application for stable and optimal operation of the power distribution system for normal and microgrid operation.

Based on different available features of ST like i) bi-direction power transfer capability, ii) integration of RES and storage at the LV and MV dc links, iii) intelligent communication network availability, this paper proposes a new prospective of ST application, called dual microgrid (DMG) operation. In a power distribution system, several feeders are connected to the common MV network through the individual CPTs. One of the CPTs in the power system is replaced by the ST. In the proposed DMG operation, the ST operates in voltage control mode to maintain a constant balanced sinusoidal voltage at the MV terminal and provides power to the loads of other feeders connected through the CPT during the islanding operation. This operation of ST provides continuous power to the sensitive loads connected to other distribution feeders, enhances the utilization of the ST, and manages the RES and storage in a more effective way. The performance of the proposed operation of ST is verified using

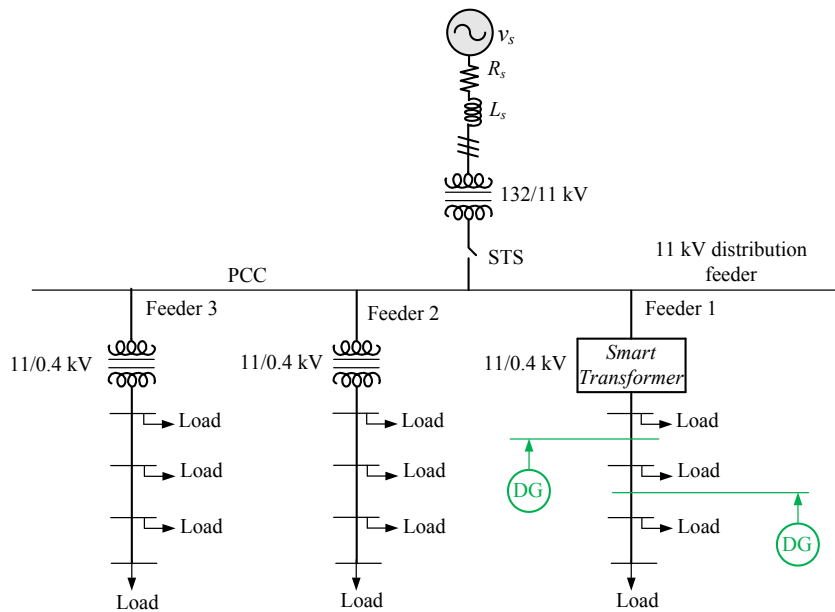


Fig. 2. Proposed power distribution system consisting of ST in dual microgrid (DMG) operation.

PSCAD simulation software in Section IV.

II. DESCRIPTION OF THE SYSTEM CONFIGURATION

Fig. 2 shows a single line representation of the ST based DMG system used for the investigation in this paper. The utility network is simplified to the Thevenin's equivalent of voltage v_s and grid impedance $R_s + jX_s$. The system consists of 11 kV, three feeder distribution subsystem and it is connected to the 132 kV utility grid. One of the CPT in the system has been replaced by the ST, whereas loads at the two of the feeders are supplied through the CPTs. Different kinds of loads such as nonlinear load, unbalanced loads, single phase loads, etc., are connected to the all three feeders. Few of the loads in all three feeders are critical loads that require continuous power supply for satisfactory operation.

With the ability to have integration of renewable energy resources, different sources such as PV, wind generation, diesel generator, different storage, etc., are assumed to be connected to the dc link of the ST. Under normal operating conditions, the DMG based ST is connected to the HV utility network through a static transfer switch (STS) as shown in the Fig. 2. The loads connected to the LV side of feeder 1 are connected to the ST. Therefore, these loads will be supplied by the ST by taking power either through the RES or utility. Moreover, the loads connected to the feeder 2 and feeder 3 are supplied by the utility or RES available at ST.

During faults in the MV network or due to intentional disconnection from the MV grid for maintenance purpose, the STS operates and disconnects the PCC from the utility mains. In this situation, the distributed generation and storage integrated at the ST is the only source of power available to feed the critical loads. In this work, the mode of operation of MV rectifier is transferred from current control mode (CCM) to voltage control mode (VCM). The MV rectifier regulates the PCC voltage at the constant value of 11 kV and

supplies uninterrupted power to the critical loads connected to the feeders 2 and 3 within the considered DMG operation. However, once the fault is cleared, the STS needs to be closed and the system needs to be re-synchronized to the utility mains to restore the normal operation of the system. Moreover, the synchronization is possible only when the utility voltages and frequencies are within the permissible range for a reasonable amount of time.

III. CONTROL AND OPERATION OF THE ST BASED DMG

In this work, a three stage smart transformer with two intermediate dc links has been used. The single phase equivalent circuit is given in Fig. 3. The operating principle of the dc-ac converter will be same throughout the operations. The dc-dc converter also continues to operate similarly with the possibility of reversal in power flow during transients. However, the operation of the MV ac-dc rectifier changes from CCM to VCM and vice-versa during the mode changeovers for the operation of DMG system. This section gives a brief idea of operation of dc-dc converter and LV ac-dc converter, along with a detailed operation of MV ac-dc rectifier.

A. Normal Operation of the ST

1) *Operation of the Rectifier:* In normal operating conditions when the MV utility voltage lies between the 0.9 to 1.1 p.u., the ST works in grid connected mode. In this mode of operation, the ST provides power to loads connected to its low voltage side and injects remaining power into the MV grid depending upon the available RES and load demand. Also, the ST provides load compensation features to compensate reactive and harmonic components of currents of other feeders. 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

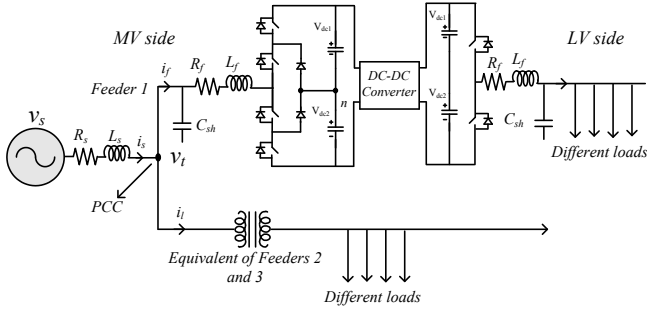


Fig. 3. Single phase ST in the proposed scheme.

[14]. The reference rectifier currents which take care of real power exchange between the ST and MV grid are computed as follows:

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

In (1), the terms v_{ta1}^+ , v_{tb1}^+ , and v_{tc1}^+ are fundamental positive sequence PCC voltages in three phases. The power P_{load1} is the average load power demand of feeder I, whereas P_{res} is power from renewable energy resources available at the dc bus of the ST. The power P_{load1} is obtained through a local communication between the MV and LV sides. Here, 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) as shown in Fig. 4 is used.

Further, the MV rectifier is also used to compensate for the unbalance and nonlinear current components of the loads connected to the feeders 2 and 3. This makes the total grid current at the MV side sinusoidal balanced and MV grid sees only a balanced resistive load 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 is as follows:

$$\begin{aligned} i_{fga}^* &= i_{l2a} + i_{l3a} - \frac{v_{ta1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2} + P_{load3}) \\ i_{fgb}^* &= i_{l2b} + i_{l3b} - \frac{v_{tb1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2} + P_{load3}) \\ i_{fgc}^* &= i_{l2c} + i_{l3c} - \frac{v_{tc1}^+}{(v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2} (P_{load2} + P_{load3}) \end{aligned} \quad (2)$$

In above equation, the currents i_{fgj}^* , i_{l2j} , and i_{l3j} are reference filter current, feeder 2 and feeder 3 current, respectively where $j = a, b, c$. Also, the powers P_{load2} and P_{load3} represent average load powers in feeder 2 and 3 respectively.

From above, it is clear that the rectifier can provide load compensation in the considered system with an effective control in addition to supplying power to loads connected to feeder 1. Therefore, the total reference currents of the rectifier

circuit (i_{rec-a}^* , i_{rec-b}^* , and i_{rec-c}^*) are given as

$$\begin{aligned} i_{rec-a}^* &= -i_{rga}^* + k_1 i_{fga}^* \\ i_{rec-b}^* &= -i_{rgb}^* + k_1 i_{fgb}^* \\ i_{rec-c}^* &= -i_{rgc}^* + k_1 i_{fgc}^* \end{aligned} \quad (3)$$

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 other feeders 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 MV dc link voltage at the constant reference voltage and maintains power flow between the MV and LV dc links. Moreover, the LV dc link voltage is maintained constant by the available renewable sources. Here, a closed loop control of dc-dc converter is achieved with an outer MV dc bus voltage control loop and inner current control loop. The advantage of the scheme is that the control of MV dc link remains unaffected with the change in operational modes of the MV rectifier. The output of this controller is phase shift angle ϕ and is shown in Fig. 5.

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 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. Therefore, the reference inverter terminal voltages are given as follows:

$$\begin{aligned} v_{lva}^* &= 230\sqrt{2} \times \sin(\omega t) \\ v_{lvb}^* &= 230\sqrt{2} \times \sin(\omega t - 120^\circ) \\ v_{lvc}^* &= 230\sqrt{2} \times \sin(\omega t + 120^\circ). \end{aligned} \quad (4)$$

B. Islanding Operation of the DMG System

1) *Operation of the Rectifier:* In a power system, the loads need to be disconnected from the MV grid either in condition of grid fault or due to scheduled maintenance in transmission system. Once the islanding is detected due to the variations in the voltage outside the limit indicated in the grid code, the part of the power distribution system that needs to be protected by supplying the continuous power is disconnected from the supply mains using the STS and the DMG operation of ST is activated. Moreover, at the same time with the help of effective communication between the different feeders and available RES and storage, the intelligent load shedding can be done.

During the islanding operation of proposed DMG system, the operational mode of MV rectifier must be changed from the current control mode to voltage control mode. For the continuous and reliable operation of the critical loads connected to the other feeder, it is essential to maintain a constant voltage at the MV point. In VCM operation of the MV rectifier, the magnitude of reference voltage at the MV terminal is set to

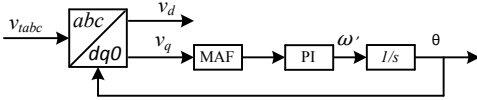


Fig. 4. Block diagram of SRF-PLL.

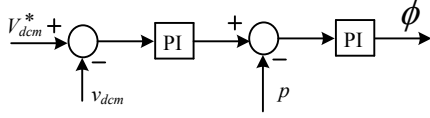


Fig. 5. Controller block diagram for dc-dc converter.

6.35 kV rms per phase (11 kV rms line-line). Therefore, the reference PCC voltages are

$$\begin{aligned} v_{mva}^* &= 6350\sqrt{2} \times \sin(\omega t) \\ v_{mvb}^* &= 6350\sqrt{2} \times \sin(\omega t - 120^\circ) \\ v_{mvc}^* &= 6350\sqrt{2} \times \sin(\omega t + 120^\circ). \end{aligned} \quad (5)$$

2) Operation of the dc-dc Converter and the Inverter:

During the islanding operation of the proposed ST based DMG system, the operation of dc-dc converter and dc-ac inverter is similar as that of the grid connected operation.

IV. PERFORMANCE EVALUATION OF ST BASED DMG SYSTEM

For evaluating the performance of the proposed ST based DMG system, the model shown in Fig. 1 is simulated in PSCAD software. The parameters of the system are given in Table I. The analysis is done under three operating conditions namely grid connected mode, islanding mode of operation, and transition from grid connected mode to islanding mode operation. Also, for testing the features of the proposed scheme, it is considered that the sufficient RES and storage is available at the dc link to support the total load demand during the islanding operation of the DMG based ST.

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
Feeder 3	Unbalanced nonlinear load
Nonlinear loads	Diode bridge rectifier loads
Linear loads	single and three phase RL loads
Rectifier parameters	$V_{dch} = 15 \text{ kV}$, $L_{fh} = 100 \text{ mH}$, $C_{dch} = 4000 \mu\text{F}$, $R_{fh} = 1 \Omega$ $C_{shh} = 0.1 \mu\text{F}$, $R_{shh} = 5 \Omega$
Inverter parameters	$V_{dcl} = 600 \text{ V}$, $L_{fl} = 5 \text{ mH}$, $C_{dcl} = 2000 \mu\text{F}$, $R_{fl} = 0.2 \Omega$ $C_{shl} = 20 \mu\text{F}$, $R_{shl} = 5 \Omega$

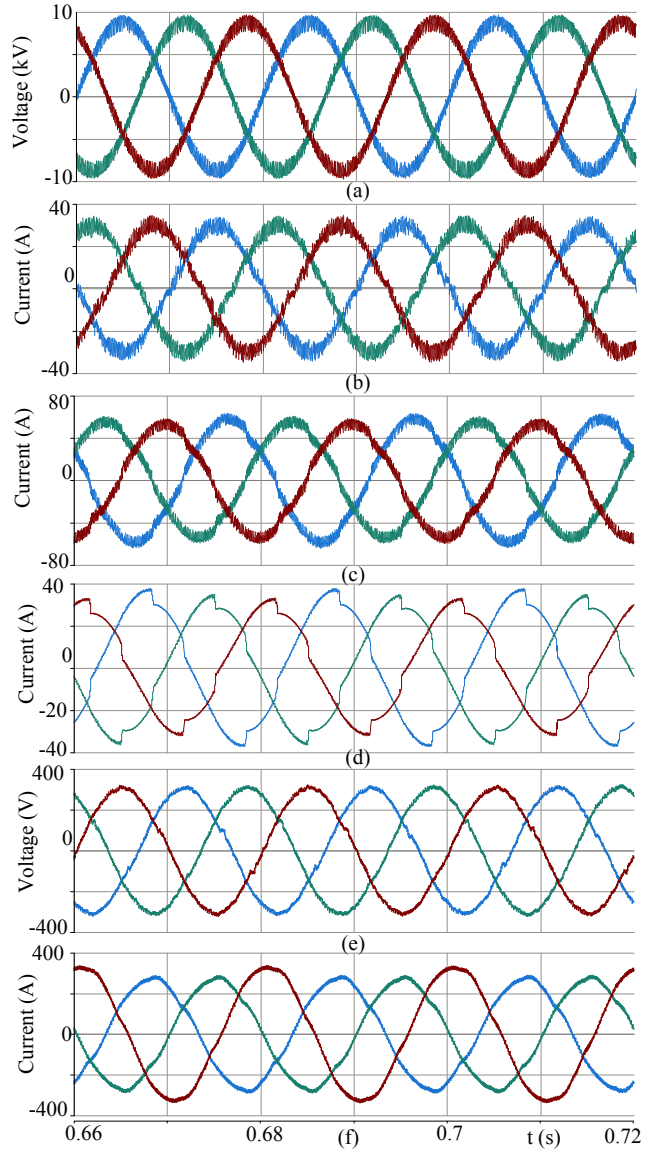


Fig. 6. Grid connected operation of proposed scheme. (a) MV PCC voltages. (b) MV grid currents. (c) MV side ST currents. (d) Total currents in feeders 2 and 3. (e) LV side ST voltages. (f) Currents drawn by loads connected to LV side of ST.

A. Steady State Grid Connected Operation

In this case, it is shown that the ST based DMG supplies available real power at the dc link into the MV grid, supplies loads connected at the LV side of the feeder 1, and additionally compensates for the reactive and harmonic components of currents drawn by the feeders 2 and 3. The steady state performance of the considered system is shown in the Fig. 6. The figure shows three phase MV PCC voltages, MV side grid currents, rectifier currents, total currents in feeders 1 and 2, and LV side voltages and currents of the feeder 1 containing ST. It can be seen that the total grid currents are balanced and sinusoidal eventhough the currents in feeders 2 and 3 are unbalanced and distorted. The reason is that the ST supplies the reactive and harmonic parts of currents drawn by other feeders to achieve these advantages. Also, grid currents are in phase opposition to the PCC voltages as the ST supplies

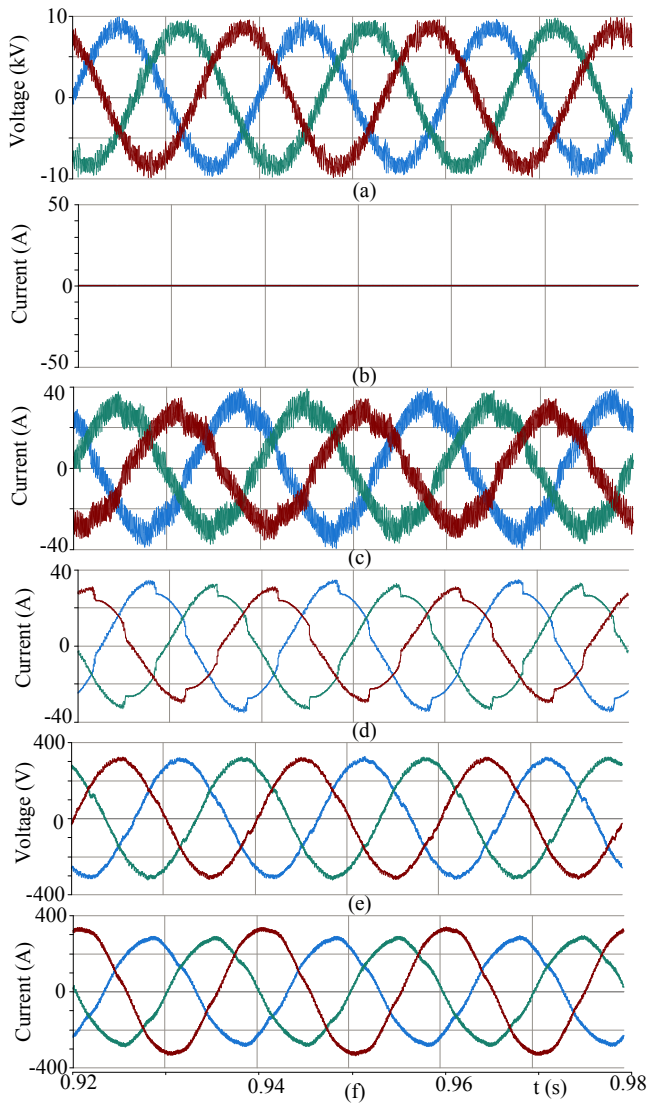


Fig. 7. Operation of proposed scheme during islanding condition. (a) MV PCC voltages. (b) MV total currents. (c) MV side ST currents. (d) Total currents in feeders 2 and 3. (e) LV side ST voltages. (f) Currents drawn by loads connected to LV side of ST.

real power into the MV grid. Moreover, a balanced sinusoidal voltage is maintained at the LV side of the ST, and the currents are drawn as per the requirements of the load. These results show that the addition of one ST in the distribution system has capability to provide bidirectional power transfer, provide load compensation at PCC, eliminate the need of power quality compensator and power factor correcting capacitors, etc.

B. Islanding Operation of DMG

In this situation, both the rectifier and the inverter of the ST operates in voltage control mode and maintains a constant balanced sinusoidal voltage at the MV and LV sides, respectively. The corresponding waveforms for this mode of operation are given in Fig. 7. The rectifier is operating in VCM and maintains a voltage of 11 kV line-line at PCC. It supplies for the loads connected to the feeders 2 and 3. This feature of the ST to support the loads connected to other feeders

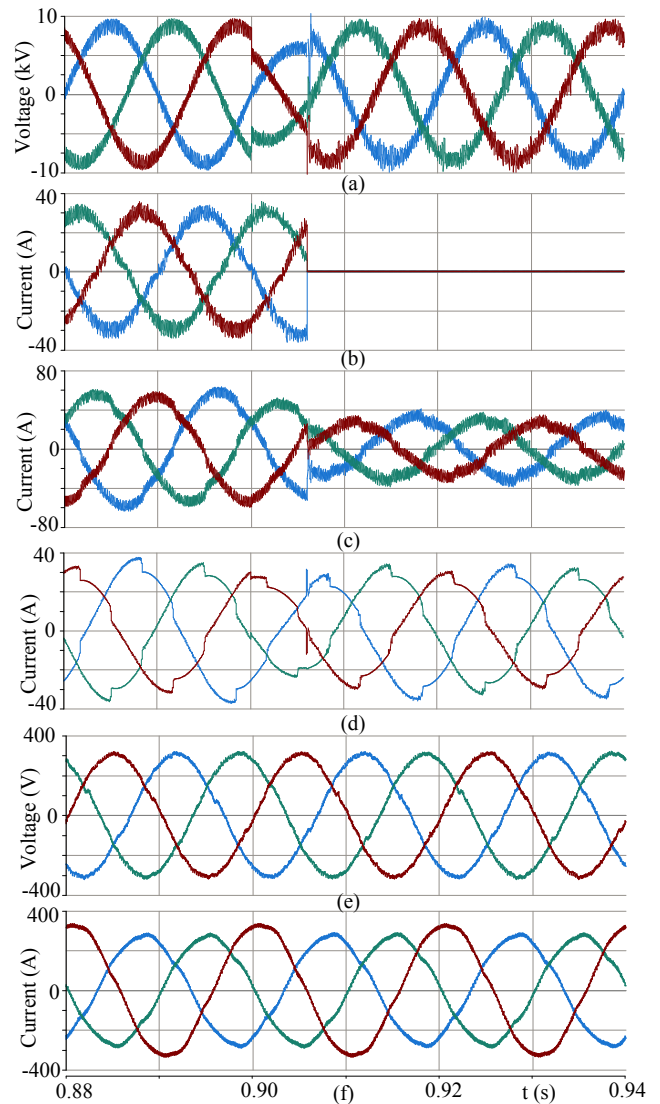


Fig. 8. Operation of proposed scheme during transient condition. (a) MV PCC voltages. (b) MV total currents. (c) MV side ST currents. (d) Total currents in feeders 2 and 3. (e) LV side ST voltages. (f) Currents drawn by loads connected to LV side of ST.

significantly improves the performance of power system and utilization of ST. Also, the loads connected to the feeders 2 and 3 remain operational even though those feeders does have necessary mean to sustain. Moreover, the inverter operation remains unchanged from the case when the ST was operating in grid connected mode. It continues to maintain a constant sinusoidal voltage at the LV side and load draws the current according to its requirements.

C. Transition from Grid Connected to Islanding Mode of Operation

This case aims to demonstrate the performance of the ST based DMG during transient operation and the corresponding waveforms are shown in Fig. 8. Before the islanding operation, the system is operating in grid connected mode and the performance is the same as that of the Fig. 6. The ST supplies real power available at the dc bus and provides load

compensation to feeders 2 and 3. At the time $t = 0.9$ s, a disturbance is created in the MV supply voltage. The control scheme detects a disturbance and the switch STS is opened. Subsequently, the control of the MV rectifier is changed from current control mode to voltage control mode operation. After the initial transients, a balanced sinusoidal voltage is maintained at the MV terminals and the loads connected at the feeders 2 and 3 are supplied by the ST. Again, the loads connected at the LV side of the ST are continuously supplied. The results indicate that the proposed ST based DMG can ensure continuous operation of the loads connected to the other feeders in addition to the loads connected to its own feeder.

V. CONCLUSIONS

This paper has proposed an ST based DMG operation in a power distribution system. In normal operation, the ST supplies available real power at the dc bus into the MV grid. Additionally, it provides load compensation at the MV side. During the voltage disturbances, the ST maintains a balanced sinusoidal voltage at the MV side and protects the sensitive loads connected to the other feeders, in addition to taking care of the loads connected to its own feeder. These advantages of the proposed DMG operation significantly improve the utilization of the ST in a power distribution system. Simulation results presented using PSCAD software validate the advantages of the proposed concept.

VI. 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] S. Bifaretti, P. Zanchetta, A. Watson, L. Tarisciotti, and J. Clare, "Advanced power electronic conversion and control system for universal and flexible power management," *Smart Grid, IEEE Transactions on*, vol. 2, no. 2, pp. 231–243, Jun. 2011.
- [2] 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 *Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on*, June 2014, pp. 2613–2619.
- [3] C. Kumar and M. Liserre, "Smart transformer for improving performance of medium voltage power distribution system," in *IEEE conference on Power Electronics for Distributed Generation (PEDG)*, June 2015.
- [4] X. She, A. Huang, and R. Burgos, "Review of solid-state transformer technologies and their application in power distribution systems," *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, vol. 1, no. 3, pp. 186–198, Sep. 2013.
- [5] P. Yong, M. Hong, Z. C. Bi, and Z. C. Feng, "A solid-state transformer with controllable input power factor and output voltage," in *Power System Technology (POWERCON), 2014 International Conference on*, Oct. 2014, pp. 2940–2944.
- [6] T. Besselmann, A. Mester, and D. Dujic, "Power electronic traction transformer: Efficiency improvements under light-load conditions," *Power Electronics, IEEE Transactions on*, vol. 29, no. 8, pp. 3971–3981, Aug. 2014.
- [7] R. Garcia Montoya, A. Mallela, and J. Balda, "An evaluation of selected solid-state transformer topologies for electric distribution systems," in *Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE*, March 2015, pp. 1022–1029.

- [8] R. Gao, I. Husain, F. Wang, and A. Huang, "Solid-state transformer interfaced pmsg wind energy conversion system," in *Applied Power Electronics Conference and Exposition (APEC), 2015 IEEE*, March 2015, pp. 1310–1317.
- [9] 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.
- [10] Y. Jie, Z. Wu, and S. Bhattacharya, "Power dispatch strategy in microgrid integrated with solid state transformer," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, July 2013, pp. 1–5.
- [11] S. Falcones, R. Ayyanar, and X. Mao, "A dc-dc multiport-converter-based solid-state transformer integrating distributed generation and storage," *Power Electronics, IEEE Transactions on*, vol. 28, no. 5, pp. 2192–2203, May 2013.
- [12] 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," *Power Electronics, IEEE Transactions on*, vol. 29, no. 8, pp. 4146–4155, Aug 2014.
- [13] Q. Wang and D. Liang, "Characteristics research of wind power generator interfaced to grid via solid state transformer with energy storage device," in *Ecological Vehicles and Renewable Energies (EVER), 2015 Tenth International Conference on*, March 2015, pp. 1–6.
- [14] A. Ghosh and G. F. Ledwich, *Power quality enhancement using custom power devices*. Kluwer academic publishers, 2002.