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Operation and Control of Smart Transformer for Improving Performance of Medium Voltage Power Distribution System

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Abstract—Smart transformer (ST) is a power electronic based transformer equipped with effective control and communication. It is expected to play a significant role in future power distribution system, however, their operational features in the medium voltage (MV) power distribution systems are yet not explored. In this paper, operation and control of ST are presented for improving its performance and operational range in a power distribution system consisting of two radial feeders in a city center. For investigating the performance of ST in above system, one conventional power transformer (CPT) is replaced by the ST whereas other feeder is continued to be supplied through the CPT. In this scheme, the ST is operated such that it makes total MV grid currents of the combined system balanced sinusoidal with unity power factor. Therefore, in addition to providing continuous and reliable operation of ST based loads, the ST can also improve the performance of the loads which are supplied by the CPT in a different feeder. Moreover, the proposed scheme eliminates the need of power quality improvement devices at the other feeder. Therefore, the scheme also makes the application of ST in the distribution system cost effective. Simulation results validate the suitability of ST in improving the performance of multiple feeder medium voltage power distribution system.

Index Terms—Smart transformer (ST), medium voltage rectifier, power distribution system.

I. INTRODUCTION

Conventional power transformers (CPTs), which provide isolation and voltage transformation, are an integral part of the electrical power distribution system from more than 100 years as these are cheap, reliable, and have high efficiency. However, increase in renewable energy sources (RES), electrical vehicles (EVs), energy storage elements, etc., need new services to the electric grid [1].

In the literature, smart transformer (ST) has been proposed as an alternate to the CPT in distribution grid [2]–[5]. The most flexible structure of the ST is made up of three-stage power converters. First stage is MV ac-dc rectifier, the second stage is MV to LV dc-dc isolation converter, and the third stage is LV dc-ac converter connected to the LV ac distribution grid. In addition to providing advantages like voltage transformation and isolation between the MV and LV sides similar to CPTs, the ST can provide several additional features like 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

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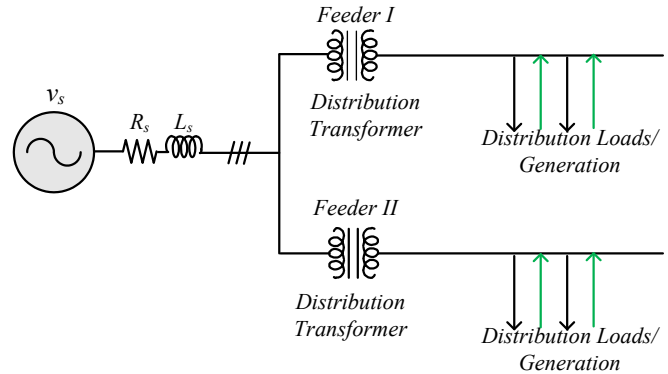


Fig. 1. A schematic of conventional power distribution system consisting of two radial feeders in a city center.

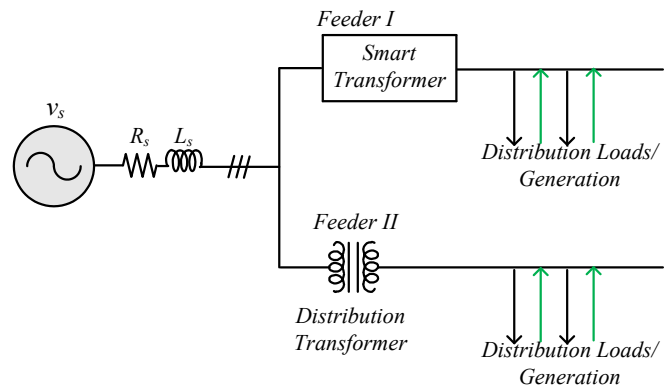


Fig. 2. Futuristic proposed power distribution system consisting of two radial feeders with one conventional power transformer is replaced by a smart transformer.

loads, availability of LV dc link for integration of distributed energy resources (DERs), etc. [6]–[9].

Continuous research is being conducted to design new circuit topologies for different stages of the ST to achieve high efficiency, reduce cost, increase voltage and power handling capability, increase fault tolerance capability, etc., and significant improvements have been achieved [10]–[14]. Moreover, being more expensive than CPTs, the ST must also have capability to provide ancillary services to the medium voltage power distribution system for making ST applications more attractive. However, the operational features of the ST in the medium voltage power distribution systems are yet not explored.

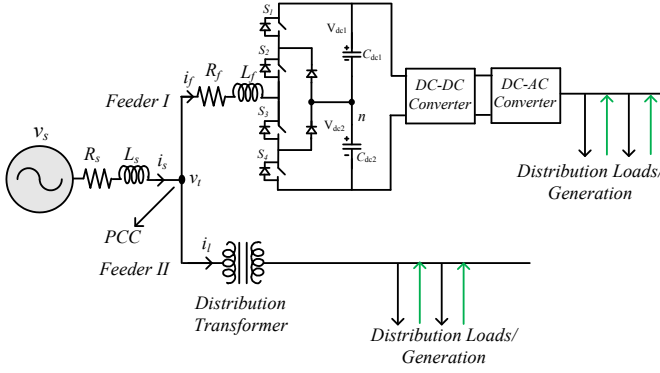


Fig. 3. Single line diagram of proposed ST based distribution system.

Fig. 1 shows an equivalent single line diagram of a conventional power distribution system consisting of two radial feeders in a city center. Both the feeders, with distributed loads and/or generation, has separate CPT for providing isolation and reducing the voltage level appropriate for the low voltage distribution system. Due to the nature of the load/generation, the system will have issues like unbalanced distorted grid currents, unbalanced distorted grid voltages, poor power factor, voltage sag, voltage swell, etc. In a future distribution grid shown in Fig. 2, the CPT in one feeder is replaced by the ST whereas another feeder uses the CPT. With the ST, the performance of the load in feeder I significantly improves as it provides advantages like balanced sinusoidal rectifier currents, balanced load voltages, no effect of grid side disturbances on loads, etc. However, the feeder II having no compensating device suffers from all aforementioned issues resulting in deterioration of load performance and violation of the grid codes.

By considering above issues, the paper aims to bring out the operational features of the ST in a two feeder system as shown in Fig. 2 to improve the performance of medium voltage power distribution system. Simulation results are presented to show the effectiveness of ST in providing load compensation in the medium voltage power distribution system.

II. DESCRIPTION OF THE CONSIDERED ST BASED POWER DISTRIBUTION SYSTEM

A detailed description of the ST based considered power distribution system is shown in Fig. 3. For simplicity, the system consisting of two radial feeder with different types of loads are chosen. However, the scheme can be extended to the multiple feeder system where ST is connected to only one feeder. In addition to providing continuous and reliable operation to feeder I, the ST also improves the performance of the loads connected at the feeder II. The ST supplies for the unbalance and harmonics of the feeder II and makes total grid current balanced and sinusoidal. In the feeder I, the ST is used to supply the load power and improve the performance of the load connected in this feeder. In this work, it is considered that the power rating of the ST is 1 MW. However, for most of the time of its operation, the ST operates much below its rated capacity. Also, utilization of the ST is further reduced as the renewable energy sources may be connected at the LV

dc link which supplies for some part of the load. Hence, it is assumed that the sufficient ST power rating is left for the improvement of the load connected to the other feeder continuing with the CPT. The loads connected to the feeder II are unbalanced nonlinear loads which draw unbalanced and highly reactive currents. The grid current, feeder I current, feeder II current, and PCC voltage are denoted by i_g , i_f , i_l and v_t , respectively. Commonly used three level neutral point clamped voltage source inverter is used to realize the MV rectifier circuit in this work. The voltages $V_{dc1} = V_{dc2} = V_{dc}$ are maintained at the both the capacitors of the rectifier for proper operation of ST.

III. DEVELOPMENT OF REFERENCE QUANTITIES IN DIFFERENT OPERATING CONDITIONS

Fig. 4 shows a control block diagram for the generation of reference current of the MV rectifier. From the control block, it can be seen that the rectifier of the ST will supply different currents into the MV grid depending upon the operating conditions. It consists of the following parts.

A. Reference Current for the Feeder I where ST is Connected

Let the ST reference currents only for the continuous operation of the loads connected to the feeder I be i_{fd1a}^* , i_{fd1b}^* , and i_{fd1c}^* in phases a , b , and c , respectively. These currents are treated as the primary reference currents of the rectifier in this work. From the block diagram shown in Fig. 4, it can be seen that these currents are drawn from the MV grid to (a) supply the loads connected to the LV side of feeder I and (b) maintain the dc link voltage at a constant value.

The rectifier currents must be in phase with the respective phase PCC voltages. Based on the instantaneous symmetrical component theory, the reference currents in this case are computed as follows [15]:

$$\begin{aligned} i_{fd1a}^* &= \frac{v_{ta1}^+}{\Delta_1^+} (P_{load1} + P_{loss}) \\ i_{fd1b}^* &= \frac{v_{tb1}^+}{\Delta_1^+} (P_{load1} + P_{loss}) \\ i_{fd1c}^* &= \frac{v_{tc1}^+}{\Delta_1^+} (P_{load1} + P_{loss}) \end{aligned} \quad (1)$$

where $\Delta_1^+ = (v_{ta1}^+)^2 + (v_{tb1}^+)^2 + (v_{tc1}^+)^2$. The terms v_{ta1}^+ , v_{tb1}^+ , and v_{tc1}^+ are fundamental positive sequence voltages in three phases. The powers P_{load1} and P_{loss} are average load power demand of feeder I and power losses in the MV rectifier circuit, respectively. The power P_{load1} can be obtained through a local communication between the MV and LV sides. 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 $e_{vdc} = 2V_{dcref} - (v_{dc1} + v_{dc2})$ 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.

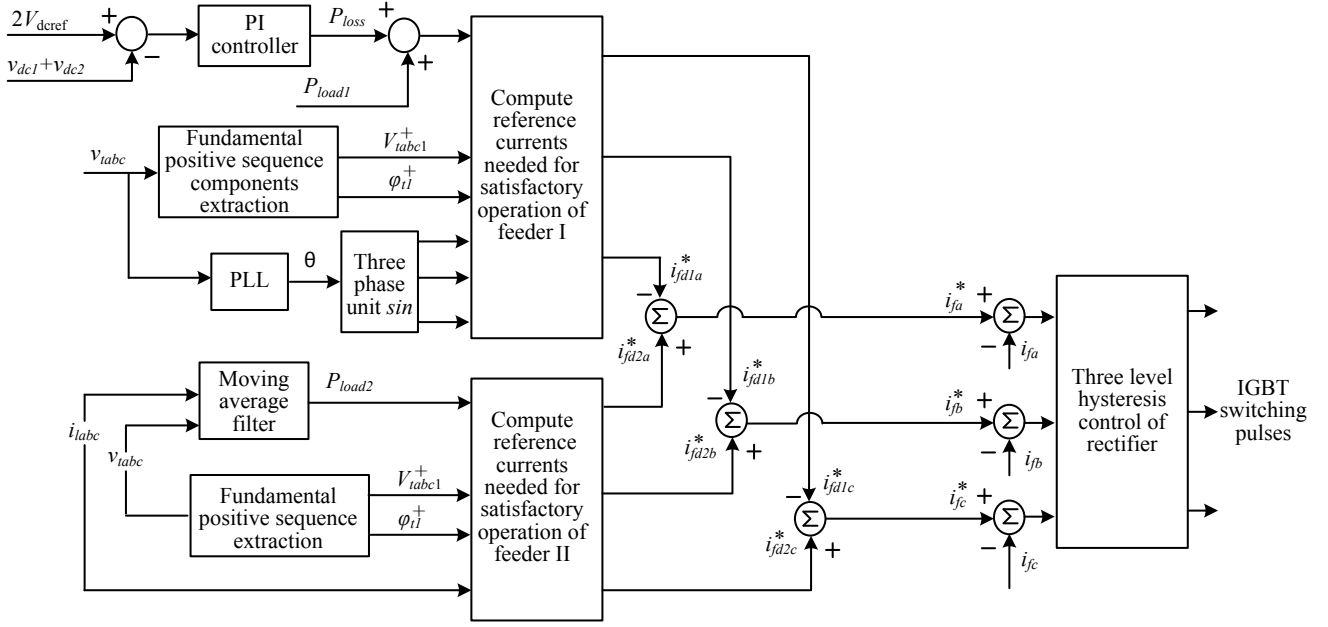


Fig. 4. Reference current generation scheme for the proposed ST operation in a distribution system.

B. Reference Currents for Improving the Performance of Loads Connected to Feeder II

The ST should supply unbalance, reactive, and harmonic component of the loads connected to the feeder II for achieving proper load compensation in MV power system. Alternately, the ST is controlled in such a way that the MV grid currents are balanced, sinusoidal, and in phase with the respective PCC voltages. Moreover, the MV grid supply only average load power requirements of the feeders I and II. Let the reference currents that need to be supplied by the rectifier to achieve these advantages be i_{fd2a}^* , i_{fd2b}^* , and i_{fd2c}^* for phases a , b , and c , respectively. Based on instantaneous symmetrical component theory, these currents are given as follows:

$$\begin{aligned} i_{fd2a}^* &= i_{la} - \frac{v_{ta1}^+}{\Delta_1^+} (P_{load2}) \\ i_{fd2b}^* &= i_{lb} - \frac{v_{tb1}^+}{\Delta_1^+} (P_{load2}) \\ i_{fd2c}^* &= i_{lc} - \frac{v_{tc1}^+}{\Delta_1^+} (P_{load2}) \end{aligned} \quad (3)$$

where P_{load2} represents the average load power requirements in the feeder II. This power is calculated using a moving average filter for better performance during transients and can have a window width of half cycle or full cycle depending upon odd or even harmonics, respectively present in the load currents. This is computed as follows:

$$P_{load2} = \frac{1}{T} \int_{t_1-T}^{t_1} (v_{ta}i_{la} + v_{tb}i_{lb} + v_{tc}i_{lc}) dt. \quad (4)$$

where t_1 and T are any time instant and system time period, respectively.

C. Total Reference Current of the MV Rectifier

For most of the time of the operation, the power system operates at the much lower than its rated power. In that case, the ST will supply for the unbalance, reactive, and harmonic loads of feeder II, in addition to supplying for loads connected to feeder I. However, if the rated loads are connected at the LV side of ST, the ST will not be able to provide load compensation. Therefore, load compensation control scheme will be deactivated during this scenario. Hence, in general, the total reference currents of the MV rectifier (i_{fa}^* , i_{fb}^* , and i_{fc}^*) are given as

$$\begin{aligned} i_{fa}^* &= -k_1 i_{fd1a}^* + k_2 i_{fd2a}^* \\ i_{fb}^* &= -k_1 i_{fd1b}^* + k_2 i_{fd2b}^* \\ i_{fc}^* &= -k_1 i_{fd1c}^* + k_2 i_{fd2c}^* \end{aligned} \quad (5)$$

In the above equation, the terms k_1 and k_2 are constants having a value of either 1 or 0. The value 1 is selected when the particular control action is activated, otherwise it will be set to 0. Therefore, depending upon the operating conditions of the power distribution system, the reference currents are selected.

Aim of this paper is to bring out the possible services the ST can provide to the multiple feeder MV distribution power system. Therefore, a simple three level hysteresis current control scheme is used to control the currents through the rectifier. In this work, we have used a three phase, three level, neutral point clamped voltage source inverter. The generation of reference currents i_{fab}^* is shown in Fig. 4. The computed reference currents are compared with the actual rectifier currents i_{fab} . The three level hysteresis current control scheme implemented for the switching pulses generation ensures that there is no successive between +1 to -1 states, as this will increase the switching frequency [16].

TABLE I
SIMULATION PARAMETERS

System quantities	Values
Source rms voltage	11 kV line-line, 50 Hz
Source impedance	$Z_s = 0.1 + j3.14 \Omega$
Feeder I loads	Average power of 500 kW
Feeder II linear loads	$S_{Ia} = 100 + j100$ kVA, $S_{Ib} = 300 + j200$ kVA $S_{Ic} = 0 + j200$ kVA
Feeder II nonlinear loads	Diode bridge rectifier loads
MV rectifier parameters	$V_{dc} = 15$ kV, $L_f = 100$ mH, $C_{dc} = 4000 \mu\text{F}$, $R_f = 1 \Omega$
Current band	± 5 V
PI controller gains	$K_p = 7$, $K_i = 0.3$

IV. SIMULATION RESULTS

This section presents the simulation results obtained after implementing appropriate control scheme in MV rectifier of the ST connected in the two feeder city center. The simulations are carried out on the PSCAD 4.5 software. The parameters of the considered system are given in Table I. The source voltage is taken as 11 kV rms line-line, 50 Hz. The feeder I draws a total average power of 500 kW from the source. In the feeder II, several linear unbalanced loads as well as rectifier loads are connected.

The steady state performance of the system when ST is not compensating for feeder II loads is shown in Fig. 5. The three phase PCC voltages, grid currents, MV rectifier currents, and feeder II currents are shown in Fig. 5(a)-(d), respectively. The MV rectifier takes currents required for the continuous operation of the loads from the source. These rectifier currents are in phase with the respective phase PCC voltages. Also, these currents are balanced and sinusoidal. As far as currents in feeder II are concerned, these are unbalanced and have significant reactive components. Therefore, the total grid currents also have significant reactive components and are unbalanced as well.

Simulated waveforms when the ST control is activated to compensate for the unbalance and reactive currents of feeder II are shown in Fig. 6. By comparing the waveforms of the PCC voltages and grid currents as given in Fig. 6(a) and (b), respectively, it can be noticed that the respective phase voltages and currents are in phase with each other. Also, the three phase grid currents are approximately balanced and sinusoidal. Therefore, the grid only supplies for the real power requirements of the loads connected to the PCC of the system. Consequently, this scheme does not require power quality improvement device to the feeder II. Fig. 6(c) shows the three phase rectifier currents. These includes the real current needed to support the loads at feeder I as well as the currents needed to compensate the loads connected to the feeder II. The loads connected to the feeder II draw currents as per the requirements and are given in Fig. 6(d).

Performance of the proposed ST based power system during transient conditions is shown in Fig. 7. The transient is created

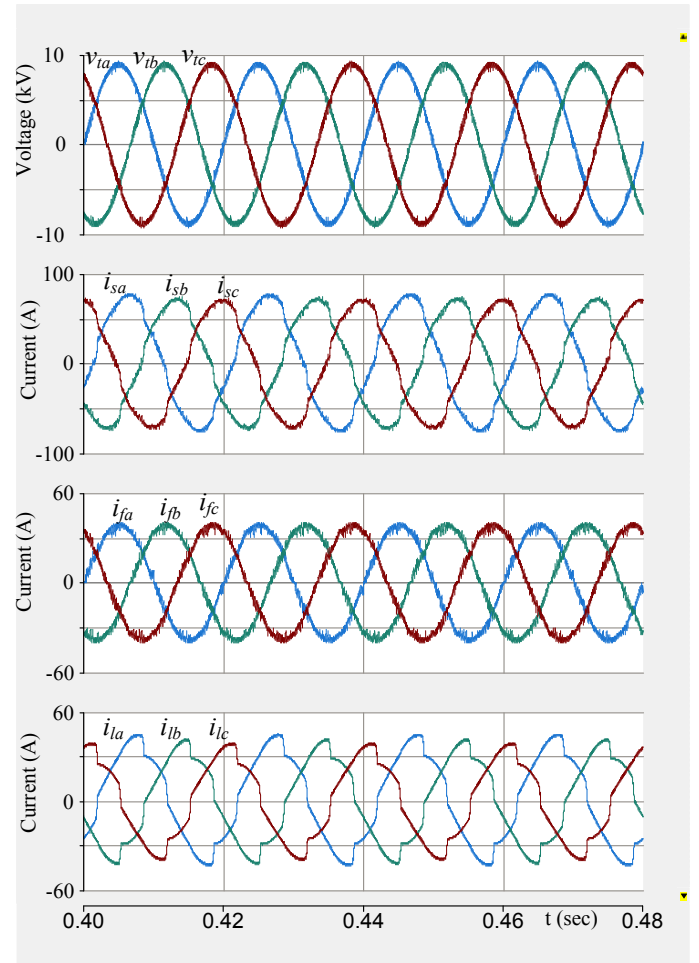


Fig. 5. Simulated waveforms when ST is not compensating for feeder II. (a) PCC voltages. (b) Grid currents. (c) MV rectifier currents (d) Feeder II currents.

by increasing the load in feeder II at time $t = 0.6$ s. It can be seen that the total grid currents are maintained balanced and sinusoidal with unity power factor at the PCC throughout the operation.

V. CONCLUSIONS

In this paper, the operation and control of a futuristic power distribution system consisting of two radial feeders with one CPT replaced by an ST is presented. It is shown that the ST can compensate for the loads connected at the feeder supplied by the CPTs, in addition to supplying their own loads. This scheme has potential to eliminate the requirement of power quality improvement devices such as STATCOM, power factor correcting capacitors, etc., connected at the second feeder. This ancillary feature in the medium voltage power distribution systems has potential to make application of ST more attractive and cost effective.

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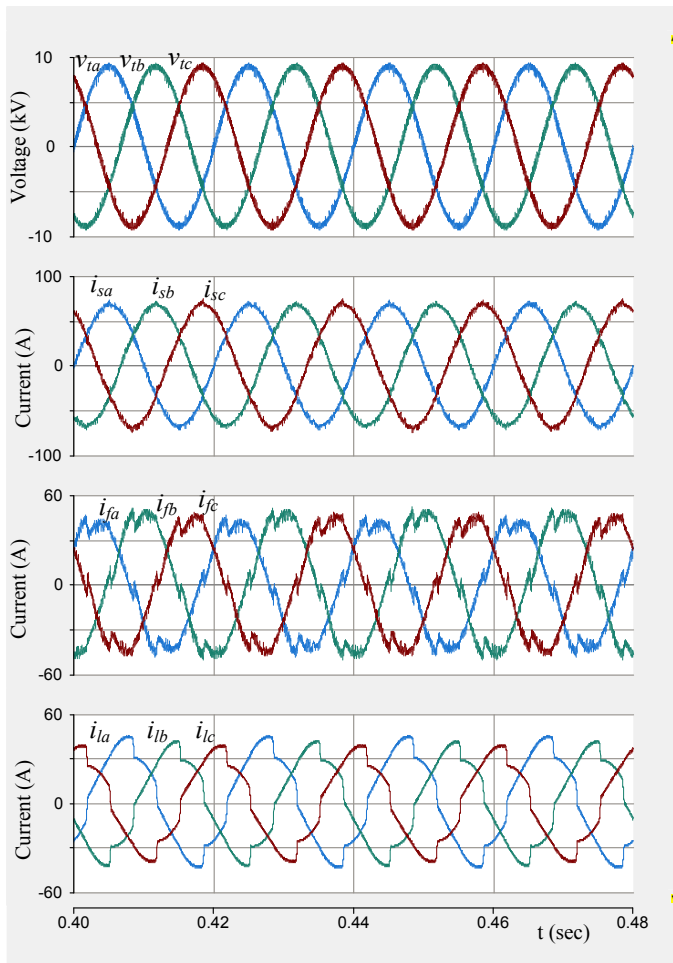


Fig. 6. Simulated waveforms when ST is compensating for feeder II. (a) PCC voltages. (b) Grid currents. (c) MV rectifier currents (d) Feeder II currents.

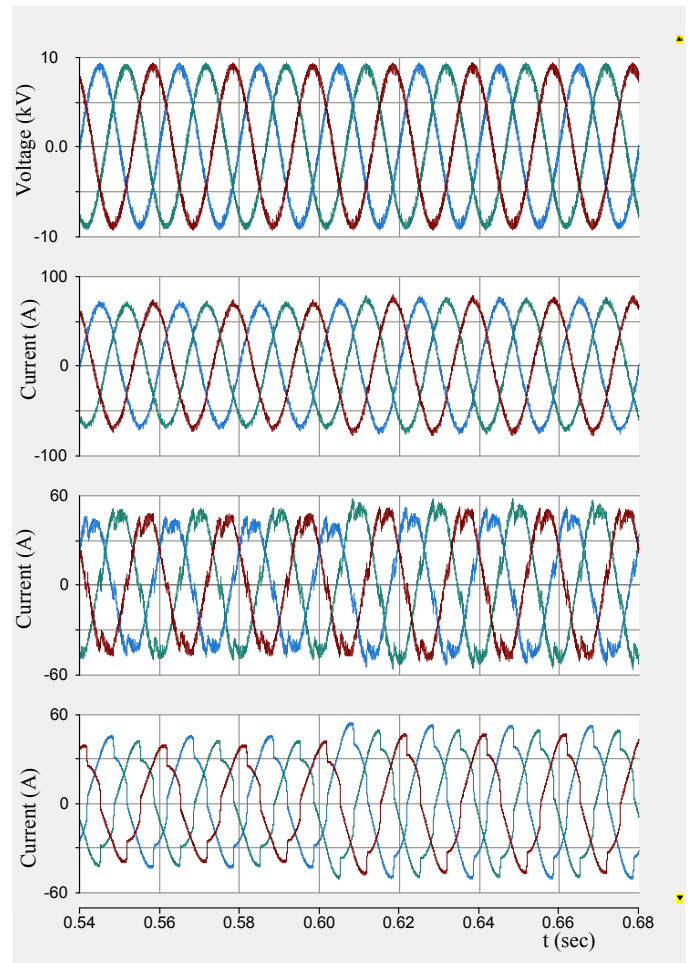


Fig. 7. Simulated waveforms during transient conditions when load in feeder II is changed. (a) PCC voltages. (b) Grid currents. (c) MV rectifier currents (d) Feeder II currents.

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