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Elektrik Dağıtım Transformatörlerinde Güç Dengesizliğinin Fotovoltaik Solar Paneller ile Azaltılması

Umut BOZAVLI[1], Mehmet YILMAZ[2], Muhammed Fatih ÇORAPSIZ[2*]

Öne Çıkanlar:

- Transformatör merkezinin çatısına GES kurulumu yapıldı
- Transformatörlerin faz dengesizliğinde iyileştirme sağlandı
- Elektrik dağıtım sisteminde yenilenebilir enerji kaynaklarının oranı artırıldı

Anahtar Kelimeler:

- Güç dengesizliği
- Dağıtım transformatörleri
- Güneş enerji sistemleri

ÖZET:

Bu makalede transformatör merkezlerinin çatısına monte edilecek fotovoltaik (PV) güneş panelleri yardımıyla üç fazlı elektrik dağıtım transformatörlerinin fazları arasında görülen güç dengesizliğinin iyileştirilmesine yönelik bir tasarım önerilmiştir. Tasarımın MATLAB/Simulink üzerinden benzetim çalışmaları yapılarak simülasyon sonuçları gözlemlenmiş ve dört transformatör merkezinden alınan gerçek zamanlı faz akım verileri ile karşılaştırılmıştır. Tasarımda geliştirilen Transfer Anahtarlayıcısı ve Kontrol Sistemi (TAKS) algoritmasında transformatörün yüzde akım dengesizlik oranı (%PCUR) tespit edilerek PV panellerden üretilen gücün transformatörün uygun fazına enjekte edilmesi sağlanmaktadır. Bu bağlantının sorunsuz şekilde gerçekleşmesi için faz kilitleme döngüsü (FKD) kullanılmaktadır. Makalede TAKS devreye girmeden önce transformatörde görülen faz dengesizliği ile TAKS devreye girdikten sonra transformatörde görülen faz dengesizliği için simülasyon sonuçları üzerinden performans analizi yapılmıştır. Erzurum, Ağrı ve Erzincan illerinde bulunan ve toplamda dört adet transformatörden alınan gerçek zamanlı veriler üzerinden yapılan simülasyon çalışmalarında, önerilen yaklaşımın transformatördeki güç dengesizliğini azaltıcı yönde etki ettiği görülmüştür. Ayrıca her bir transformatör için dağıtım sistemine yaklaşık 3.6 kW ilave enerji sağlanmaktadır. Bunun yanında transformatörlerden çekilen ortalama akım değerlerinin de azaldığı gözlemlenmiştir.

Mitigation of Power Unbalance in Electrical Distribution Transformers with Solar Photovoltaic Panels

Highlights:

- Solar Power Plant (SPP) was installed on the roof of the transformer center
- Improvement in power unbalance in transformers has been achieved
- The rate of renewable energy sources in the electricity distribution system has been increased

Keywords:

- Power unbalance
- Distribution transformers
- Solar power systems

ABSTRACT:

In this article, a design is proposed to improve the power unbalance between the phases of three-phase electricity distribution transformers with the help of photovoltaic (PV) solar panels to be mounted on the roof of transformer centers. Simulation studies of the design were performed via MATLAB/Simulink and simulation results were observed and compared with real-time phase current data from four transformer centers. In the Transfer Switcher and Control System (TSCS) algorithm developed in the design, the percentage current unbalance rate (PCUR%) of the transformer is determined and the power produced from the PV panels is injected into the appropriate phase of the transformer. Phase lock loop (PLL) is used to ensure this connection occurs smoothly. In this study, performance analysis was made based on simulation results for the phase unbalance seen in the transformer before TSCS was activated and for the phase unbalance seen in the transformer after TSCS was activated. In simulation studies conducted on real-time data taken from a total of four transformers in Erzurum, Ağrı and Erzincan provinces, it was seen that the proposed approach had a reducing effect on the power unbalance in the transformer. In addition, approximately 3.6 kW of additional energy is provided to the distribution system for each transformer. In addition, it has been observed that the average current values drawn from the transformers has also decreased.

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This study was produced from Umut BOZAVLI's Master's thesis.

INTRODUCTION

The demand for the use of electrical energy is increasing worldwide and the electrical energy sector makes significant contributions to the economic growth and development of countries around the world (Strielkowski et al., 2021). For this reason, it is of great importance to deliver electrical energy to consumers in an uninterrupted, high-quality, cost-effective and safe manner (Yurdabak & Şekkeli, 2014).

The generation, transmission and distribution of electrical energy is generally done with three-phase systems. During the first generation, the current, voltage and phase angle values of these three phases are balanced with each other (El-Hawary, 2008). However, while the produced energy is delivered to consumers, factors such as the formation of harmonics in voltage and currents, sudden voltage drops, decrease in power factor and power unbalance prevent the quality transfer of power (Barutçu & Erduman, 2023).

Balance in electricity distribution systems; it is defined as the effective values of the current and voltage flowing through the phases in the system being equal and the angles between the phases being 120° (Douglass et al., 2016). Unbalance is when current and voltage effective values and phase angles are different from each other (Rodriguez et al., 2015). Balanced and unbalanced current and voltage phasors are shown in Figure 1.

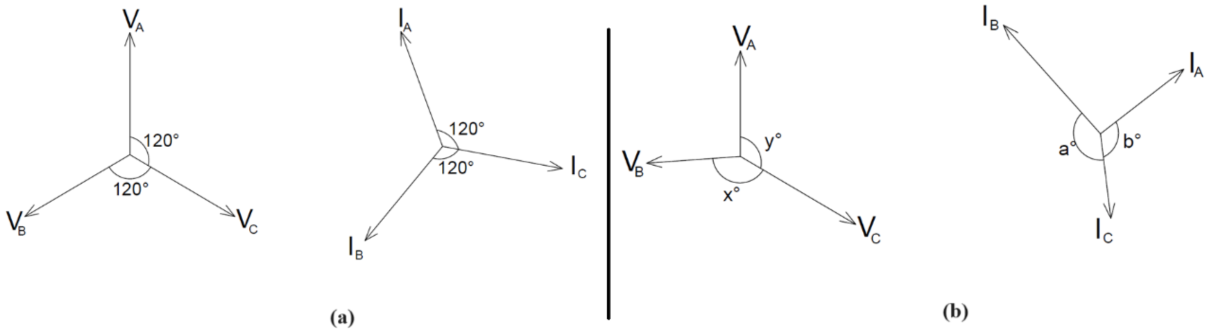

Figure 1. (a) Balanced current and voltage phasors (b) Unbalanced current and voltage phasors

The Institute of Electrical and Electronics Engineers (IEEE) uses the phase-neutral voltage to measure voltage unbalance (Pillay & Manyage, 2001). To express the V_{pn} phase-neutral voltage and the V_{ave} average value of voltages, the percentage voltage unbalance rate (PVUR%) is calculated as in Equation 1 (Özan, 2020).

$$\text{PVUR\%} = \frac{Max\left(\left|V_{pn} - V_{ave}\right|\right)}{V_{ave}}.100 \quad (1)$$

Phase unbalance occurs in three different ways: voltage unbalance, current unbalance and power unbalance. Although current and power unbalance are calculated in a similar way to voltage unbalance but current and power unbalance do not have any limitations in the standards like voltage unbalance (Özan, 2020).

According to European Standards, it is stated that voltage unbalance should be limited to 2% of the 10-minute measurement average at low voltage (LV) level (Markiewicz & Klajn, 2004). However, voltage unbalance is increase up to 10% in rural areas depending on load distribution (Najafi, 2016).

An average unbalance of 20% in phase currents causes an unbalance of 2-3% in phase voltages (Ay, 1989). In this way, it is possible to establish a relationship between voltage unbalance and current unbalance.

The most important reason for phase unbalance is single-phase loads that are not evenly distributed in the grid (Jouanne & Banerjee, 2001). Moreover intensive single phase supply of residential subscribers in distribution grids, faults occurring in single phase, large power industrial loads, unbalanced distribution of load in grid designs, impedance differences due to unequal conductor distances can cause unbalance in the system (Najafi, 2016).

Phase unbalance causes various negativities. It causes the useful life of the facilities and equipment in the distribution systems to expire prematurely before their economic life expires. Overheating occurs in transformers. Residual currents occurring in unbalanced systems flow through the neutral conductor in star-connected systems, causing energy loss (Kongtrakul et al., 2023). Unbalanced current and voltage draws cause negative and zero components of current and voltage in distribution systems (Jouanne & Banerjee, 2001). Unbalanced currents cause increased vibration and mechanical stress in transformers. Transformer efficiency decreases. Transformers create noise during operation. In unbalanced loads, harmonic currents of three and multiples interfere with the grid signals (Cuong & Nhu, 2022).

This article presents the Transfer Switcher and Control System (TSCS) algorithm for reducing phase unbalance in transformers. The algorithm is based on the principle of determining the percentage current unbalance rate (PCUR%) of the transformer and in line with this determination, the power obtained from the photovoltaic (PV) panels installed on the roof of the building type transformer center is injected into the appropriate phase of the transformer. In the article, the change between the phase unbalance seen in the transformer before TSCS is activated and the phase unbalance seen in the transformer after TSCS is activated is investigated. The performance of the proposed algorithm is simulated via MATLAB/Simulink and demonstrates the effectiveness of TSCS in reducing the PCUR% seen in the transformer. The proposed algorithm has potential application in existing and newly established electrical distribution transformer centers. With this design it is aimed to;

- Mitigation of the power unbalance that occurs in the LV output of electrical distribution transformers inside the transformer center buildings,
- Effective and efficient use of roofs of transformer centers,
- Contributing to the reduction of carbon emissions,
- Increasing the rate of renewable energy sources in the electricity distribution system with the help of photovoltaic (PV) panels.

MATERIALS AND METHODS

In this study, a system design consisting of;

- A transformer center with a length of 7.5 meters and a width of 2.5 meters,
- 6 solar panels with 600 W power (it was calculated according to the dimensions of the transformer centers roof)
- Distribution transformer (MV/LV),
- Loads connected to the grid,
- DC -DC boost converter circuit,
- Unipolar PWM switched single-phase DC-AC inverter,
- Transfer switcher and control system (TSCS),
- Maximum power point tracking (MPPT) circuit,
- Proportional resonance (PR) controller circuit,
- LCL low-pass filter circuit,
- Phase lock loop (PLL) circuit.

The control scheme of the design is shown in Figure 2.

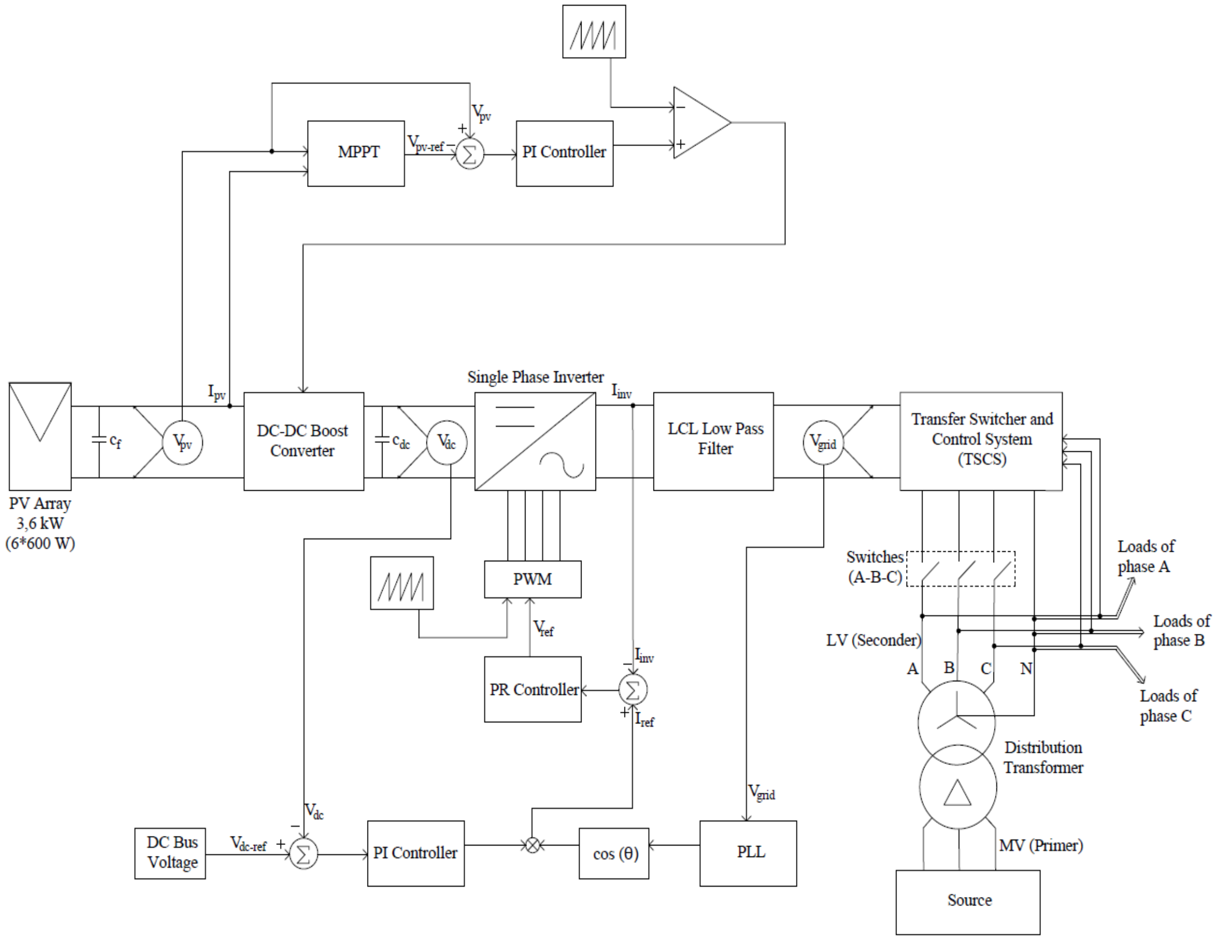

Figure 2. The control schema of designed system

The basic values to be used in this simulation are shown in Table 1 where V_{grid} refers to the effective value of the phase-neutral voltage of the phases in the LV grid, P_{pv} refers to the maximum power to be obtained from solar panels that can fit on the transformer center roof, V_{dc} refers to the voltage level at which the string voltage is desired to be increased, T and G represent the operating conditions of PV panels, I_{rip} refers to the limitation used in filter circuit design.

Table 1. The basic values used in the simulation

Parameters	Icon	Values
Main Voltages	V_{grid}	231 V
Rated Power	P_{pv}	3.6 kW (6*600 W)
DC Bus Voltage	V_{dc}	400 V
PV Array Maximum Power Voltage	V_{mpp}	205.8 V
PV Array Open Circuit Voltage	V_{oc}	249 V
Main Frequency	f	50 Hz
Maximum Current Ripple Rate	I_{rip}	20%
Ambient Temperature	T	25°C
Solar Irradiation	G	1000 W/m^2

This study is designed as a grid-connected system. Depending on the size of the transformer center, 6 solar panels with a power of 600 W can be mounted on the roof of the building. In this way, it is planned to obtain 3.6 kW of power. PV panels are connected to each other in a single parallel string.

The maximum power voltage of the array consisting of solar panels is 205.8 V and the DC bus voltage is determined as 400 V. Therefore, a DC-DC boost converter circuit was used to increase the input voltage from 205.8 V to 400 V.

MPPT circuit was used to monitor the maximum power point of the PV panel output depending on changing environmental conditions such as temperature and solar irradiation (Bollipo et al., 2020). Various algorithms are used in the MPPT circuit (Ilyas et al., 2018). The increasing conductivity algorithm was preferred in the research. The increasing conductivity algorithm is based on the comparison of the conductivity (I/V) and increasing conductivity (dI/dV) of the PV panel, and its mathematical expression is included in Equation 2 (Keskin, 2014).

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V} \tag{2}$$

DC signals given to the single-phase inverter input from the DC-DC boost converter circuit are converted into AC signals with the help of the inverter. AC signals depend on the conduction and cut-off times of the semiconductor elements in the inverter (Fidan, 2020). Unipolar PWM switching inverter is preferred in the design because it reduces switching losses and has higher efficiency (Namboodiri & Wani, 2014). However, PWM technique causes the production of unwanted harmonics. A low-pass LCL filter circuit is used at the inverter output to filter these harmonics through a filter circuit and keep the total harmonic distortion (THD) rate within the limits (Cossoli et al., 2018).

The synchronized reference plane method (d-q method) was used to enable the PLL to synchronize the signals generated from PV panels with the grid signals. Thanks to this method, the power produced from PV panels can be injected into the desired phase of the transformer. The park transform is used to transform the generated variables V_α and V_β into the rotating axis set variables V_d and V_q. The parking transformation matrix is given in Equation 3 (Yılmaz et al., 2021).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{3}$$

Since the traditional PI controller has some disadvantages for current control in the system, a proportional resonance (PR) controller has been recommended. PR controllers can achieve zero steady-state error because they can provide infinite gain at the fundamental frequency. The proposed controller is implemented around a fixed frequency to regulate both the positive and negative components of the current (Sagiraju et al., 2017).

The difference of this study from other studies is the use of TSCS in the design. In TSCS algorithm first determines the average current value of the A, B, C phases. The effective average value calculation of phase currents is shown in Equation 4, where I_{TR-a}, I_{TR-b} and I_{TR-c} refers to phase currents and I_{TR-ave} refers to the average value of the phase currents.

$$I_{TR-ave} = \frac{I_{TR-a} + I_{TR-b} + I_{TR-c}}{3} \tag{4}$$

TSCS calculates the absolute value of the maximum deviation amount in phase currents and enables the determination of the highest deviation amount between these three values. The PCUR% value is obtained by dividing the highest deviation amount determined by the average current value. If the PCUR% value is below 5%, the system continues to be monitored by TSCS. If the PCUR% value is above 5%, the highest phase current of the transformer is determined by TSCS and the switch for this phase is closed. Thus, the energy obtained from PV panels is transferred to this phase. The flow chart of the proposed TSCS system is presented in Figure 3.

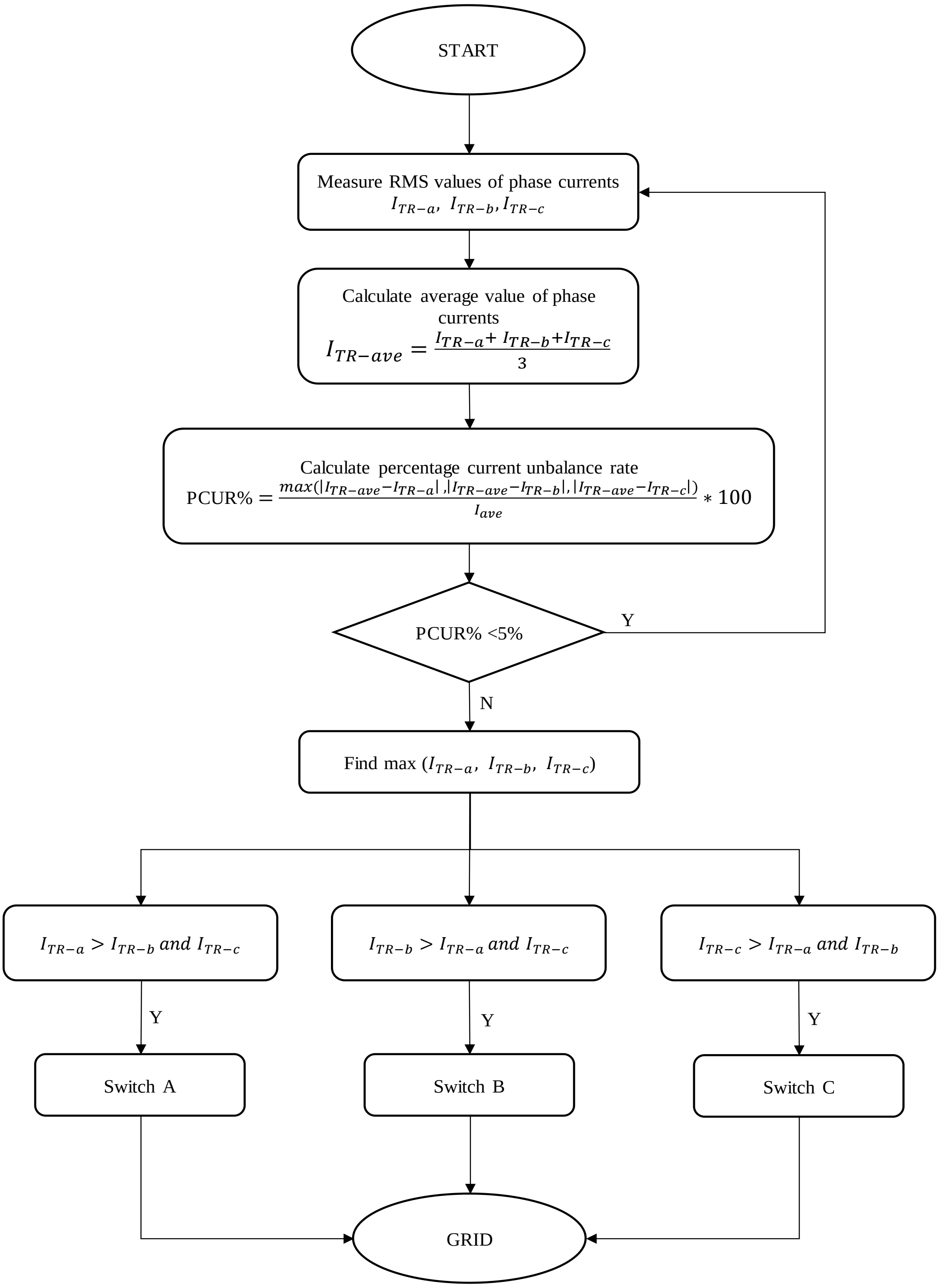

Figure 3. The flow chart of TSCS

Since a phase lock loop (PLL) is used in the system, TSCS is integrated into the phase angle and frequency values of whichever phase is switched. After this stage, TSCS continues to monitor the grid and switches between phases A, B or C to distribute the generated energy according to the change in current values.

RESULTS AND DISCUSSION

In this study, real-time data was taken from the LV outputs of four transformers located in Erzurum, Erzincan and Ağrı provinces. The simulation of the distribution system created using these data was made in the MATLAB/Simulink environment. The changes of the phase currents obtained from these simulation studies against time are presented. It has been observed that TSCS uses the data received from the system to transfer energy to the phase that draws the most current and reduces phase unbalances. The current values before and after transferring energy to any phase by TSCS switching are given in a comparative table.

The first simulation study was carried out on the data of the 160 kVA transformer in Erzincan, taken on 27 November 2023 at 12:00, and the effective values of the instantaneous currents seen at the LV outputs of the transformer are shown in Table 2.

Table 2. First transformer LV output instantaneous current values

Phase currents	Current Values (Real) (Before TSCS was activated)	Current Values (Simulation) (After TSCS was activated)
I_{TR1-A}	65.67 A	55.58 A
I_{TR1-B}	47.99 A	47.99 A
I_{TR1-C}	55.91 A	55.91 A

The PCUR% value measured before TSCS was activated was found to be 16.16%. First transformer current signals of phases A, B and C before TSCS was activated are seen in Figure 4.

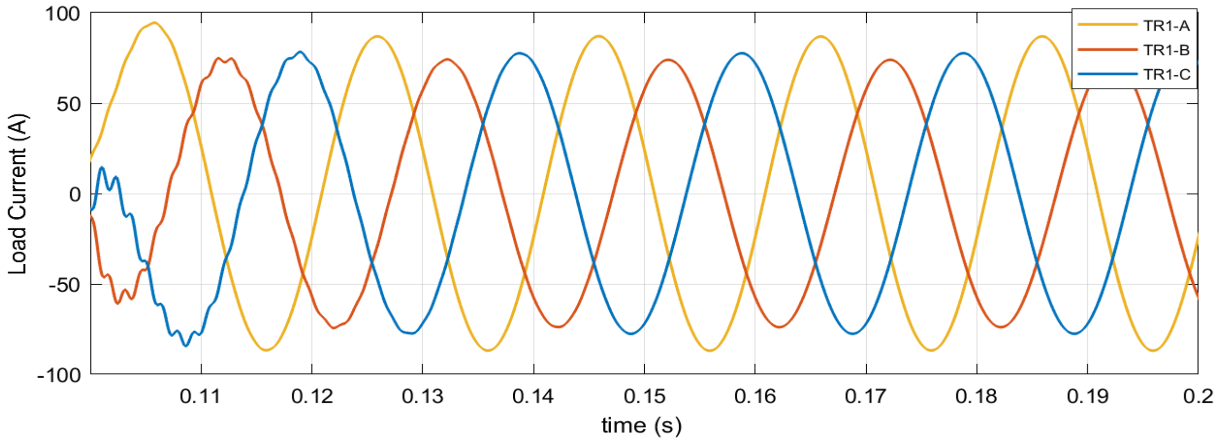

Figure 4. First transformer current signals before TSCS was activated

After TSCS was activated it is determined that the phase that draws the most current from the transformer is phase A. TSCS sends a command to the transfer switch to connect the power produced by the PV panels to phase A, and switch A is energized. Thus, the I_{TR1-A} value decreases from 65.67 A to 55.58 A, the $I_{TR1-Ave}$ value decreases from 56.52 A to 53.16 A and the PCUR% value decreases from 16.16% to 9.72%. The signals seen in the first transformer phase currents after TSCS is activated are shown in Figure 5.

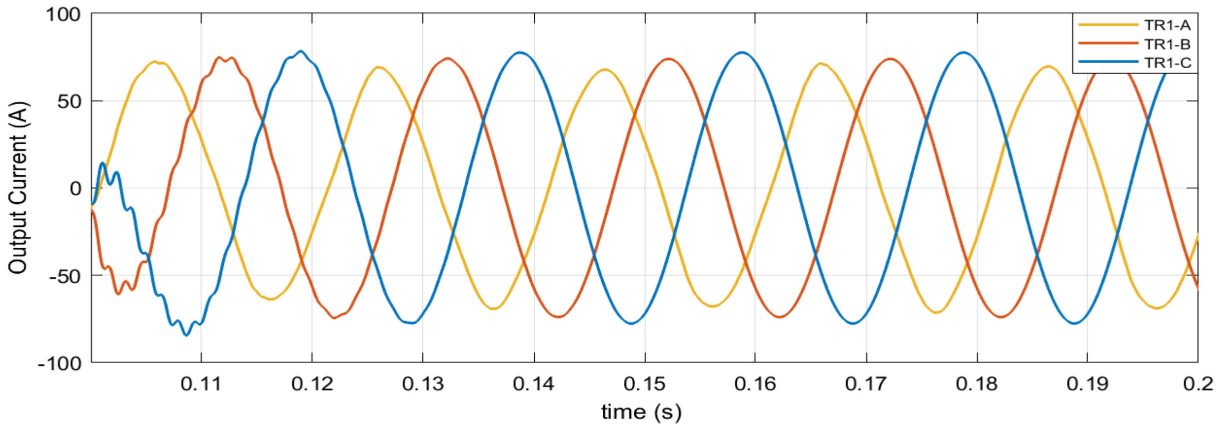

Figure 5. First transformer current signals after TSCS was activated

In the other simulation study, data taken from the 160 kVA transformer in Erzurum province on 18.12.2023 at 16:00 was used. The effective values of the instantaneous currents seen at the LV outputs of the second transformer are seen in Table 3.

Table 3. Second transformer LV output instantaneous current values

Phase currents	Current Values (Real) (Before TSCS was activated)	Current Values (Simulation) (After TSCS was activated)
I_{TR2-A}	36.51 A	36.51 A
I_{TR2-B}	54.16 A	43.64 A
I_{TR2-C}	42.26 A	42.26 A

Before TSCS was activated, the PCUR% value was measured as 22.17%. The second transformer current signals before TSCS is activated are presented in Figure 6.

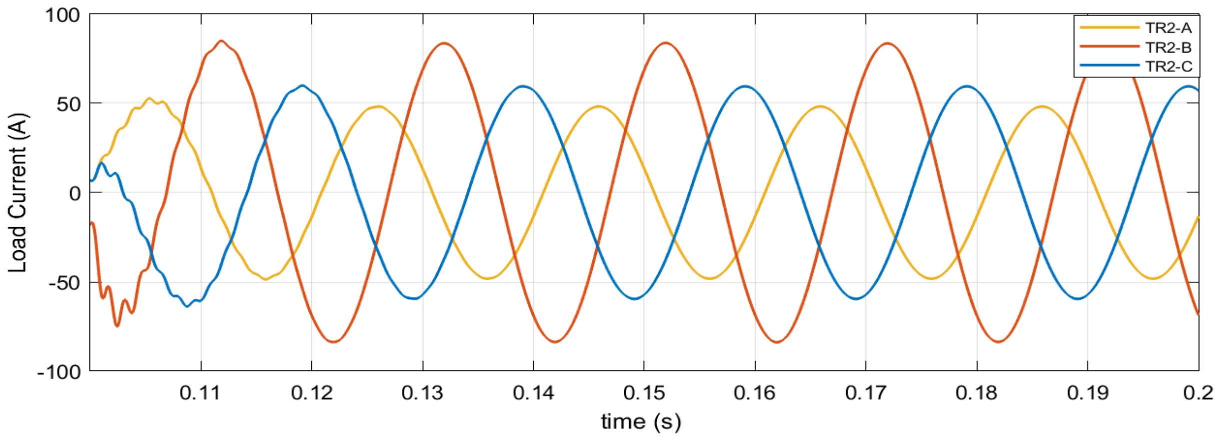

Figure 6. Second transformer current signals before TSCS was activated

In order to demonstrate the effectiveness of the proposed method, real-time data from Erzurum province was used. It was observed that the current values of the phases before TSCS activation for this transformer were 36.51 A, 54.16 A and 42.26 A, respectively. When TSCS was activated, it was observed that the phase currents were 36.51 A, 43.64 A and 42.26 A and the current value in phase B was reduced. Thus, the $I_{TR2-Ave}$ value was reduced from 44.31 A to 40.8 A, thus reducing the PCUR% value from 22.17% to 10.53%. The current changes seen in the second transformer phase currents after TSCS is activated are shown in Figure 7.

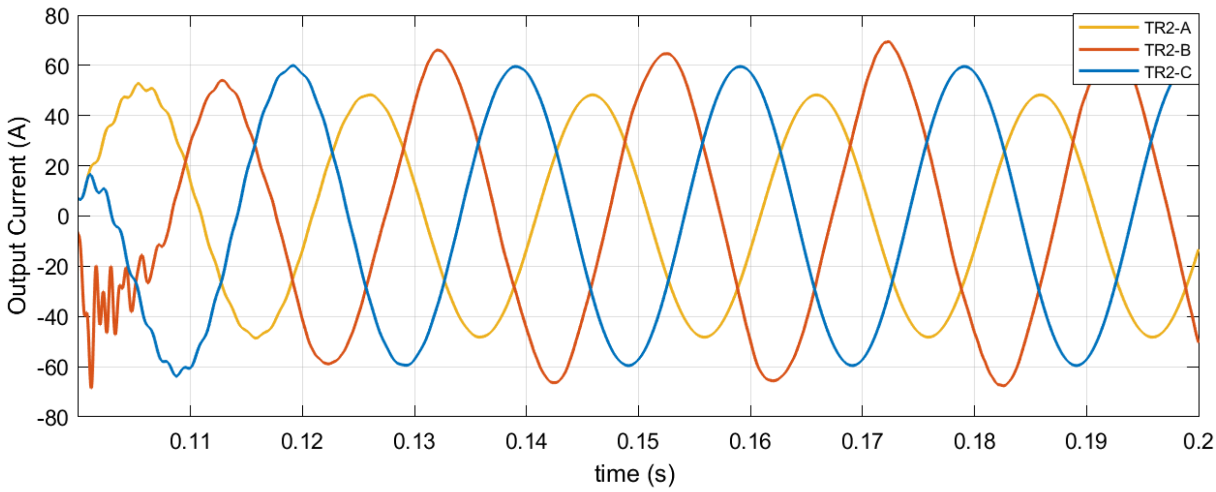

Figure 7. Second transformer current signals after TSCS was activated

The third simulation study was carried out on December 18, 2023 at 16:00 with data taken from the 160 kVA transformer. The effective values of the instantaneous current seen at the LV outputs of the transformer located in Ağrı are seen in Table 4.

Table 4. Third transformer LV output instantaneous current values

Phase currents	Current Values (Real) (Before TSCS was activated)	Current Values (Simulation) (After TSCS was activated)
I_{TR3-A}	18.33 A	18.33 A
I_{TR3-B}	18.05 A	18.05 A
I_{TR3-C}	42.03 A	31.62 A

Before TSCS was activated, the PCUR% value of the transformer was observed to be 60.80%, and the current signals of phases A, B and C are shown in Figure 8.

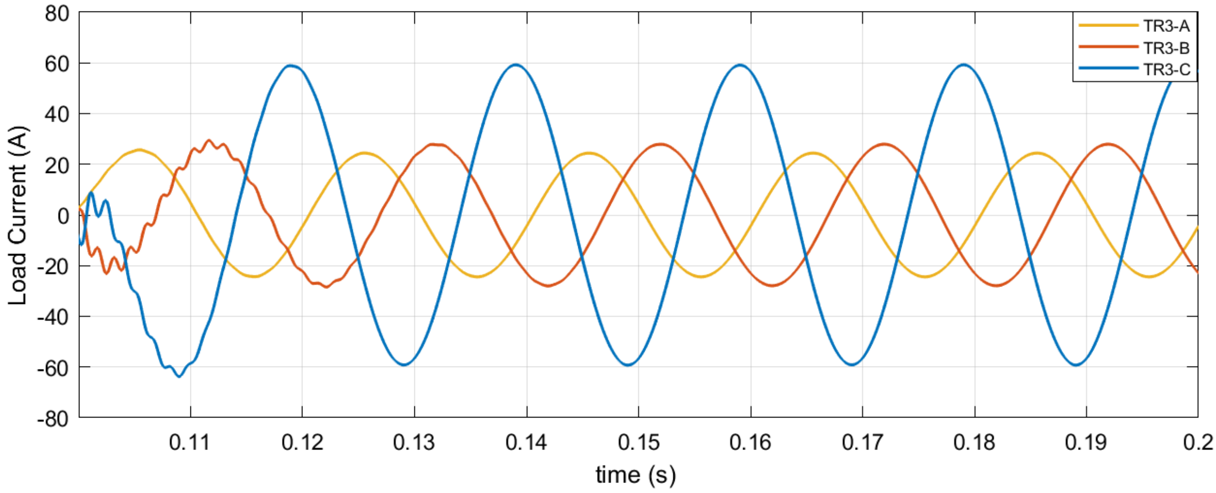

Figure 8. Third transformer current signals before TSCS was activated

TSCS was activated because the PCUR% value was above 5% in the measurement made with the TSCS algorithm. In the measurement, it was determined that the phase that draws the most current from the transformer is phase C. TSCS enabled the power generated from PV panels to be injected into this phase by energizing the C switch. Thus, the I_{TR3-C} value decreased from 42.03 A to 31.62 A and the PCUR% value decreased from 60.80% to 39.5%. The signals seen in the third transformer phase currents after TSCS is activated are shown in Figure 9.

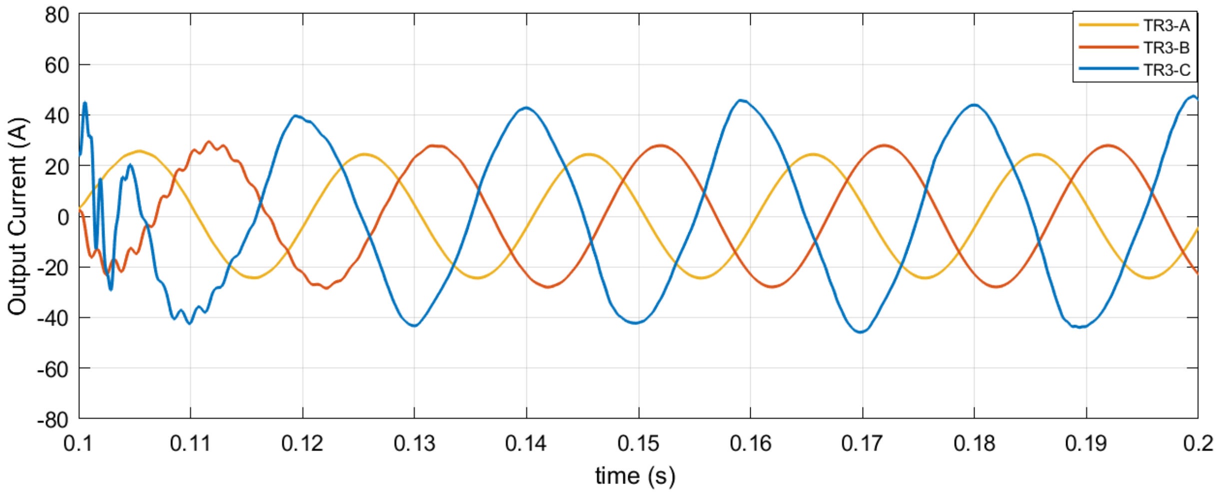

Figure 9. Third transformer current signals after TSCS was activated

The fourth transformer for which the simulation study will be carried out is located in Erzurum and has a power of 160 kVA. The current values seen on the secondary side of the transformer at 12:00 on 18.12.2023 are presented in Table 5.

Table 5. Fourth transformer LV output instantaneous current values

Phase currents	Current Values (Real) (Before TSCS was activated)	Current Values (Simulation) (After TSCS was activated)
I_{TR4-A}	20.46 A	20.46 A
I_{TR4-B}	44.14 A	31.4 A
I_{TR4-C}	24.79 A	24.79 A

The PCUR% value measured before TSCS was activated was 48.14%. The current signals of phases A, B and C before TSCS is activated are shown in Figure 10.

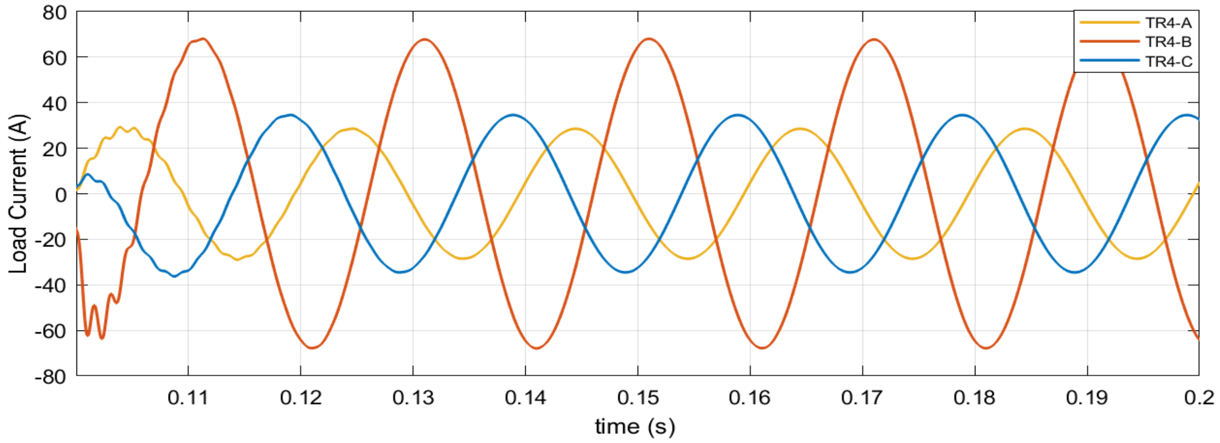

Figure 10. Fourth transformer current signals before TSCS was activated

Since the PCUR% value is above the specified limit, TSCS has determined that the phase that draws the most current from the transformer is phase B. According to this determination, switch B was energized and the power produced from the PV panels was injected into this phase and the I_{TR4-B} value decreased from 44.14 A to 31.4 A, the $I_{TR3-ave}$ value decreased from 29.80 A to 25.55 A and the PCUR% value decreased from 48.14% to 22.9%. The signals seen in the fourth transformer phase currents after TSCS is activated are seen in Figure 11.

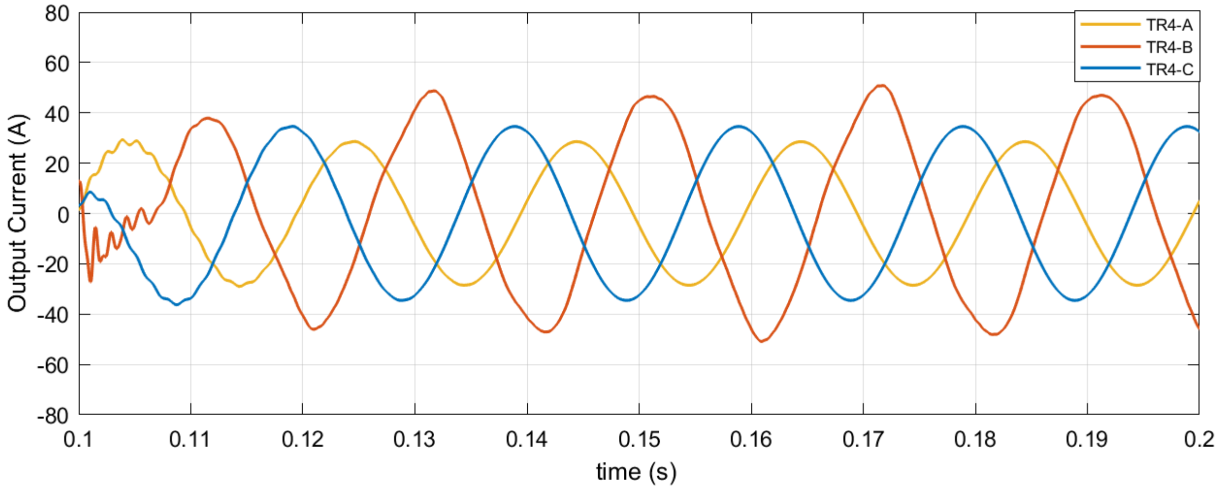

Figure 11. Fourth transformer current signals after TSCS was activated

The data obtained is compiled and Table 6 shows the improvement rates in PCUR% of transformers.

Table 6. Improvement in PCUR% values of transformers

Transformer	Current Values (A) (Before)	Current Values (A) (After)	PCUR% (Before)	PCUR% (After)	Improvement in PCUR%
First Transformer	I_{TR1-A}= 65.67 A I_{TR1-B}= 47.99 A I_{TR1-C}= 55.91 A	I_{TR1-A}= 55.58 A I_{TR1-B}= 47.99 A I_{TR1-C}= 55.91 A	16.16%	9.72%	6.44%
Second Transformer	I_{TR2-A}= 36.51 A I_{TR2-B}= 54.16 A I_{TR2-C}= 42.26 A	I_{TR2-A}= 36.51 A I_{TR2-B}= 43.64 A I_{TR2-C}= 42.26 A	22.17%	10.53%	11.64%
Third Transformer	I_{TR3-A}= 18.33 A I_{TR3-B}= 18.05 A I_{TR3-C}= 42.03 A	I_{TR3-A}= 18.33 A I_{TR3-B}= 18.05 A I_{TR3-C}= 31.62 A	60.80%	39.5%	21.30%
Fourth Transformer	I_{TR4-A}= 20.46 A I_{TR4-B}= 44.14 A I_{TR4-C}= 24.79 A	I_{TR4-A}= 20.46 A I_{TR4-B}= 31.4 A I_{TR4-C}=24.79 A	48.14%	22.9%	25.24%

CONCLUSION

In this article, a design that will improve the phase unbalance in the transformer with the help of SPP to be installed on the roof of the transformer center is proposed. In order to test the TSCS algorithm proposed in the design, simulation studies were carried out using data from four different transformers Erzurum, Ağrı and Erzincan provinces. According to the results obtained from the simulation studies, it was observed that there was a significant improvement in the PCUR% values of the transformers for all the above-mentioned cases with the application of the proposed method.

Thanks to the design, it will be possible to use the idle roofs of transformer buildings effectively and efficiently, provide cleaner energy input to the electricity distribution system, reduce carbon emissions and eliminate the negative effects of phase unbalance in transformers. Additionally, this design has the potential to be implemented in existing and new substations both in our country and around the world.

In future studies, it is aimed to design a system that will simultaneously transfer power to each phase in the distribution grids in proportion to the unbalance, by using the power obtained from PV panels placed on transformer roofs. With this system, it will be ensured that the distribution transformer output currents have equal amplitude for all phases. In this way, parallel to the balanced current draw from the transformer windings, heating of the transformer windings will be prevented and losses will be reduced.

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Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author's Contributions

The authors declare that they have contributed equally to the article.

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