IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 17 November 2023, accepted 3 December 2023, date of publication 5 December 2023, date of current version 13 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3339782

RESEARCH ARTICLE

Tap Staggering Analysis and Effects on the Adaptive Protection System in Networks With Renewable Energy Sources

HAKAN KASAP[1,2], MIKAIL PURLU[3], BELGIN EMRE TURKAY[1], AND REZA GANJAVI[4], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Istanbul Technical University (ITU), 34469 Istanbul, Turkey
[2]Siemens Türkiye, 06800 Ankara, Turkey
[3]Department of Electrical and Electronics Engineering, Sivas Cumhuriyet University, 58140 Sivas, Turkey
[4]Siemens AG, 90459 Nürnberg, Germany

Corresponding author: Hakan Kasap (kasapha@itu.edu.tr)

This work was supported by the Siemens Türkiye Research and Development Center.

ABSTRACT Increasing the penetration of renewable energy sources as distributed generation in modern power grids presents several challenges, including voltage level issues and protection system failures resulting from bidirectional power flow and changing network dynamics. Voltage limit violations could potentially damage the utility equipment and lead to power quality problems. Innovative Volt/VAr control methods, such as tap staggering, can be used to overcome these problems. Tap staggering utilizes circulating current between parallel transformers to provide reactive power absorption from the network. However, the absorption of reactive power by the primary substation using tap staggering poses a potential risk to the protection system, particularly the Directional Overcurrent protection scheme with Load Blinder. This could lead to failures or nuisance trips during normal load conditions. In this study, a real power system is modeled using real data in PSS CAPE with 120 scenarios generated through tap staggering application, all based on 24-hour demand/wind generation data. The Tap Staggering Macro and Adaptation Protection Macro were developed for the purpose of analyzing these scenarios. The study demonstrates that tap staggering effectively mitigates overvoltage issues on the transmission system by absorbing reactive power. Although there is an increase in active power losses when tap staggering level is increased on the parallel transformers, the power loss remains within reasonable limits. Despite its benefits, tap staggering has been found to affect the Directional Overcurrent with Load Blinder protection scheme, limiting power transfer generated through wind turbines in the distribution network. This results in changes to the protection scheme's Directional Overcurrent Pickup, Load Blinder Resistance, and Load Blinder Alpha parameters, requiring adaptation in all scenarios. After adaptation, the protection system operates reliably, guaranteeing efficient and unrestricted transmission of distributed generation power to the grid.

INDEX TERMS Adaptive protection, DOC with load blinder protection scheme, Volt/VAr control, renewable energy sources, PSS CAPE.

I. INTRODUCTION

Fossil fuel consumption is a major factor in the increase of greenhouse gas emissions, resulting in climate change and global warming. The Intergovernmental Panel on Climate Change has identified human activities, such as the burning of fossil fuels, as the primary cause of global warming [1]. The urgent need to reduce fossil fuel consumption and transition to renewable energy sources has been highlighted by many experts and organizations worldwide [2]. Increasing renewable energy sources (RES) in the network is leading to radical changes in the traditional networks. While traditional

The associate editor coordinating the review of this manuscript and approving it for publication was Alon Kuperman.

transmission and distribution networks have a unidirectional power flow, the spread of RESs has led to a bidirectional power flow, resulting in changing network dynamics. Thus, it causes voltage changes in the power grid, resulting in major protection system problems such as protection blinding, false tripping, and unintentional islanding [3]. In networks where the generation from different points of the RES density network participate, when the demand on the consumer side decreases, the voltage level in the network increases as the demand/generation balance shifts to the generation side. This is undesirable in that the voltage levels in the grid violate the lower and upper limits set by the regulators. An increase in the voltage level can damage the utility equipment, and power quality problems can occur because of the voltage drop. To solve to this problem, the voltage should be controlled by certain methods. Chen, Li et al., present the tap staggering method to solve the overvoltage problems in transmission systems during low demand periods without installing reactor or VAr compensators. The results show that the tap stagger method applied to transformers successfully absorbs reactive power and mitigates voltage problems [4]. In the other study, the tap staggering method was compared with the installation of shunt reactors according to the economic and dynamic effect on the transmission voltages. It has been found that the tap staggering method is more economical, and it reduces voltage damping and overshoot during the transients [5]. The Customer Load Active Services (CLASS) project has created a demand response and reactive power absorption capability through aggregated voltage regulation by tap staggering. The main benefits of the CLASS is unlocking the distribution network load demand flexibility without causing any negative impact on customers and providing the lowest cost of fast reserve service from a distribution network to a transmission network. When the CLASS method is applied to all 60 primary substations for 600 hours per year, this method provides up to 129 MVAr of reactive power absorption and saves up to 3336 tons of CO_2 per year and it also defers huge reinforcement cost by eliminating the need to install new equipment [6], [7]. Rousis, Pipelzadeh, et al., demonstrate the effectiveness of tap staggering application on 132/33 kV parallel transformers in the distribution network to mitigate the overvoltage problem on the 400 kV transmission system in southeast England [8]. Due to the increased amount of RES generation in the network, the demand needed by consumers can be exceeded. To avoid generator power output restrictions and enable exceeded reverse power flow to the upstream network, it is essential to investigate methods for increasing export power levels to the upstream network. To solve this restriction, the proposed way is modifying or replacing the existing Directional Overcurrent (DOC) protection scheme without the need for conventional network reinforcement and DOC with Load Blinder protection scheme implemented to the network as a result of the trial [9], [10]. However, while the tap staggered transformers absorb reactive power from the subtransmission grid to improve bus overvoltage during low demand conditions, there could be a potential risk on the DOC with Load Blinder protection scheme which leads to protection fails or a nuisance trip during normal load. This operation causes the power factor angle and reverse current changes that result in the DOC and Load Blinder static parameters to be no longer accurate, and it could be led to a loss of power flow capacity released by DOC with Load Blinder protection scheme. For this reason, the effect of the tap staggering on the DOC with Load Blinder protection scheme will be examined and the static parameters will be adapted depending on this effect. Thus, in grids with high RES penetration, power capacity will be released at lower cost thanks to adaptive protection and will have a lower carbon impact compared to conventional methods.

In this study, to solve the overvoltage issues mentioned in the literature, an innovative Volt/VAr control method tap staggering has been studied by applying it to the 33/11 kV parallel transformers in the distribution substation to absorb reactive power from the transmission network. Besides, the effects of the applied tap staggering Volt/VAr control method on the DOC with Load Blinding scheme are investigated based on the changing demand/generation profile, RES generation capacity and various tap staggering levels.

In this paper, the authors propose the following novelty and contributions resulting from the study:

- 120 scenarios are generated with 24 hours demand/generation profile, with 5 different tap positions for each hour. In all scenarios, tap staggering is implemented to analyze its effect on bus voltages, reactive power absorption and power loss in the parallel transformers.
- The Tap Staggering Algorithm and Macro automatically analyze the effects of tap staggering on the network system and retrieve the results.
- The overvoltage issue in the 132 kV transmission network during periods of low demand has been resolved by applying tap staggering to three pairs of parallel transformers in the 33/11 kV distribution network, resulting in reactive power absorption.
- Considering the effects of the tap staggering Volt/VAr control method on the protection system, concluded that the DOC with the Load Blinder protection scheme is affected in all scenarios since the tap stagger application alters the short circuit currents and active-reactive powers measured on the relay which has DOC with Load Blinder scheme.
- Enhanced the Adaptive Protection algorithm and macro to adapt the relay parameters of the DOC with Load Blinder scheme based on the application of tap staggering.
- Through the Adaptation Protection Macro, the parameters of $I>_{DOC}$, R_{LB}, and α for the DOC with Load Blinder scheme have adjusted according to demand/generation and varying tap staggering scenarios.
- With the adapted DOC with Load Blinder scheme parameters;

- The protection system operates reliably with the adapted protection scheme.
- The power generated by the RESs in the distibution network can be delivered to the transmission system more efficiently without any restriction by the protection scheme and tap staggering operation.

To validate this study; Section II provides an explanation of the tap staggering method. Then, DOC with Load Blinder scheme and adaptive protection is demonstrated to solve the reverse power restriction problem in Section III. Following this, the network model is created based on the 24-hour demand/generation profile and varying tap levels in the parallel transformers, and the macros used to analyze the scenarios and results are presented in Section IV. All analysis results are evaluated in Section V. Ultimately, the study is concluded in Section VI.

II. TAP STAGGERING AS A VOLTAGE AND VAR CONTROL METHOD

The power systems have been designed to function within specific voltage limits. Constant changes in loads and generations within the network system can result in voltage violations which could potentially harm the network's equipment. For this reason, network operators have the responsibility of maintaining voltage within specific limits [11]. Voltage control is typically achieved by controlling the generation, absorption, and flow of reactive power throughout the system, as the impedance of the network's components are mostly reactive [12]. The network systems have different components for controlling Volt/VAr, including generating units such as synchronous generators, producers or consumers of reactive power like active and passive compensation devices and regulating transformers. The automatic voltage regulators are equipped with synchronous generators that adjust the field excitation to control the voltage at the connected terminal buses [13]. Depending on the natural electrical characteristics of AC power systems, active compensation devices such as synchronous capacitors, static VAr compensators and STATCOMs generate or absorb reactive power as required by the AC system to stabilize transmission systems, improve voltage regulation, correct power factor, and correct load imbalances [14].

Traditional voltage control methods may no longer be adequate for passive systems experiencing unidirectional power flow [15]. The transmission network voltage problem has grown more dynamic and may arise in various periods or different locations due to the integration of large-scale intermittent distributed renewable generation [16]. If multiple devices require installation at different points throughout the system, the associated costs will be substantial. Moreover, the installation of permanent passive VAr compensators may not be the most cost-effective solution to addressing temporary voltage problems. To overcome these problems, the tap staggering method is proposed as an alternative for voltage control service [4].

A. TAP STAGGERING APPLICATION

Tap staggering is an active method of Volt/VAr control that utilizes parallel transformers already in existence to provide reactive power absorption services for transmission systems during periods of low demand. The method aims to mitigate overvoltage in the upstream network by aggreating VAr absorption from many parallel transformer pairs. The Tap Staggering Optimal Control System receives the request for reactive power absorption from the upstream network to determine the optimal number of parallel transformers and tap levels for minimizing power losses and taps switching operations. The tap levels determined through optimization of the parallel transformer's On-Line Tap Changer (OLTC) are transmitted via the communication network to the relevant substations' Automatic Voltage Control (AVC) relays. AVC relays send a command to the appropriate OLTCs of the parallel transformers to set the required tap levels to the OLTC to make the tap change. For the implementation of this technique, transformers must have an On-Load tap changer. In addition, tap difference level of the each parallel transformers should be limited to 4 in order to prevent undue power losses and overloading of transformers [17].

B. CIRCULATING CURRENT BETWEEN THE PARALLEL TRANSFORMERS

The operation of two parallel transformers with staggered taps in Fig. 1 is demonstrated.

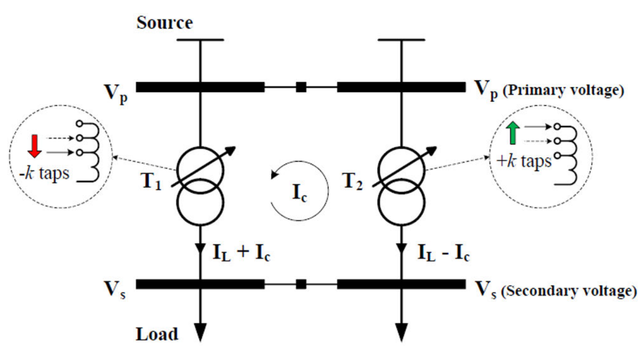

FIGURE 1. Tap staggering operation at a substation with parallel transformer pair [18].

Both transformers T_1 and T_2 have On-Load tap changers in their primary windings, with tap changer levels remaining in their original positions initially. The tap changer level is reduced by k steps on T_1, while it is increased by k steps on T_2 to establish the tap stagger pattern. Assuming identical tap changer parameters for both transformers, the primary voltage V_p referenced to the secondary side of T_1 and T_2 in equations (1) and (2) where k represents an offset value from the initial tap position TAP_0, n_m indicates the nominal transformer ratio that the tap stagger introduces and ΔTAP represents the tap position increment per step of the OLTC.

$$V_1 = \frac{V_p}{n_m(TAP_0 - k\Delta TAP)} \quad (1)$$

$$V_2 = \frac{V_p}{n_m(TAP_0 + k\Delta TAP)} \tag{2}$$

The circuit diagram for the transformer's secondary sides is depicted in Fig. 2.

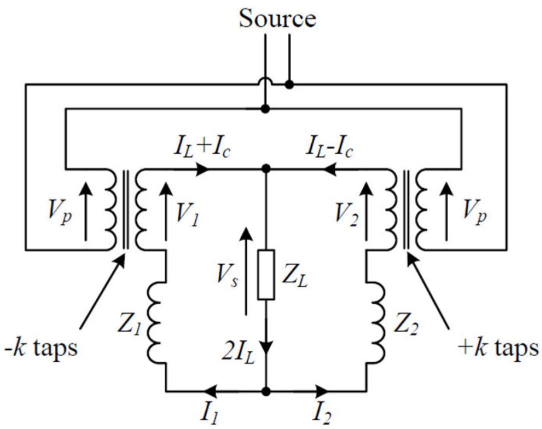

FIGURE 2. Equivalent circuit of tap stagger on the secondary side of the transformer [19].

The secondary currents of transformers T_1 and T_2 are:

$$I_1 = \frac{V_1Z_2 + (V_1 - V_2)Z_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \tag{3}$$

$$I_2 = \frac{V_2Z_1 - (V_1 - V_2)Z_L}{Z_1Z_2 + (Z_1 + Z_2)Z_L} \tag{4}$$

As shown in Fig. 2, Z_1 and Z_2 represent the transformer impedance on the secondary sides of T_1 and T_2, respectively, and Z_L indicates the equivalent load impedance. In the typical scenario where $Z_L \gg Z_1$ and $Z_L \gg Z_2$ [19], the secondary currents of transformers T_1 and T_2 can be calculated using the following equation:

$$I_1 \approx \frac{V_1Z_2 + (V_1 - V_2)Z_L}{(Z_1 + Z_2)Z_L} \tag{5}$$

$$I_2 \approx \frac{V_2Z_1 - (V_1 - V_2)Z_L}{(Z_1 + Z_2)Z_L} \tag{6}$$

The circulating current, which is a part of both I_1 and I_2, appears in the system according to (7).

$$I_c = \frac{(V_1 - V_2)}{(Z_1 + Z_2)} \tag{7}$$

I_1 and I_2's remaining parts can be expressed in (8),(9).

$$I_{L1} = \frac{V_1Z_2}{(Z_1 + Z_2)Z_L} \tag{8}$$

$$I_{L2} = \frac{V_2Z_1}{(Z_1 + Z_2)Z_L} \tag{9}$$

When the value of k is small and limited to a range of +4 and −4 from the 0 tap position and $I_{L_1} \approx I_{L_2} = I_L$, thus $I_1 = I_L + I_c$ and $I_2 = I_L - I_c$. The corresponding phasor diagram is obtained as shown in Fig. 3. The transformer leakage reactance in Z_1 and Z_2 consume additional reactive power because of the circulating current.

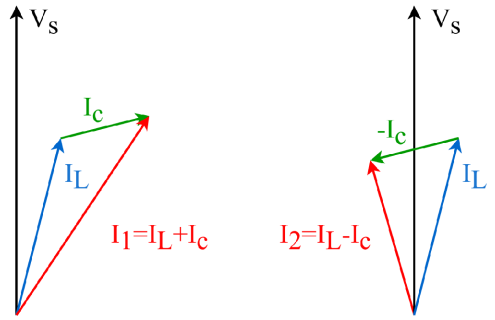

FIGURE 3. Phasor diagram of the currents in the transformer T_1 and T_2 [18].

C. SECONDARY SIDE VOLTAGE OF THE TRANSFORMER

Assuming that both transformers possess the same impedance, for instance $Z_1 = Z_2 = Z$, the secondary voltage of the transformer can be calculated as follows:

$$V_S = (I_1 + I_2)Z_L = \frac{V_1 + V_2}{2} \tag{10}$$

$$V_S = \frac{V_p}{n_m\left(TAP_0 - \frac{k^2\Delta TAP^2}{TAP_0}\right)} \tag{11}$$

If the parallel transformers are tapped in a small range k restricted by +4 and −4 from the 0 tap position, the secondary voltage of the transformer V_S stays nearly constant as stated in (11). As a result, the voltages and demands of the network connected to the secondary side of the transformer will remain unaffected during the tap staggering operation.

D. REACTIVE POWER ABSORPTION AND ACTIVE POWER LOSS IN TAP STAGGERED PARALLEL TRANSFORMERS

Additional reactive power consumption ΔQ_c resulting from tap staggering operation through circulating current Ic can be defined in (12), where X_t represents the transformer leakage reactance and Z_t is the transformer impedance pu value.

$$\Delta Q_c = 2I_c^2X_t = \frac{X_t(k\Delta TAP\frac{V_p}{n_m})^2}{Z_t^2(TAP_0^2 - k^2\Delta TAP^2)^2} \tag{12}$$

The extra active power loss ΔP_c resulting from tap staggering in the transformer is shown in (13), where R_t is the transformer winding resistance.

$$\Delta P_c = 2I_c^2R_t = \frac{R_t(k\Delta TAP\frac{V_p}{n_m})^2}{Z_t^2(TAP_0^2 - k^2\Delta TAP^2)^2} \tag{13}$$

III. DIRECTIONAL OVERCURRENT LOAD BLINDER ADAPTIVE PROTECTION APPLICATION

As the amount of renewable generation connected to the distribution grid increases, the power flow becomes bi-directional, resulting in power flow from the distribution network to the transmission network. Delivering the power generated by RESs to the transmission network with unrestricted maximum capacity enables the most efficient use

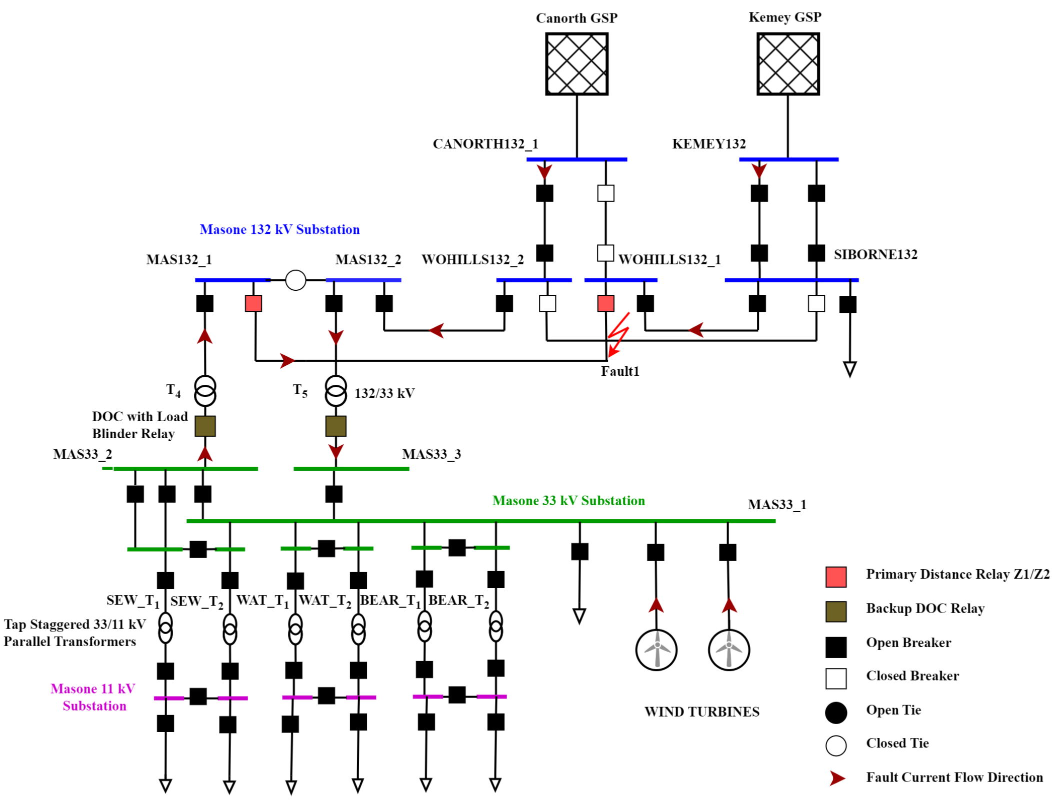

FIGURE 4. Short-circuit current flows during 132 kV remote-end faults in the Masone 132 kV substation open tie configuration.

of generation capacity. Nonetheless, protection equipment may impose a restriction on the transformers' maximum thermal capacity when supplying reverse power to the upstream system. To overcome this limitation, the protective scheme "DOC with Load Blinder" is applied [20]. The protection scheme must be calculated and adapted at specific time periods under changing network dynamics to eliminate reverse power flow restrictions and ensure reliable operation.

A. DIRECTIONAL OVERCURRENT WITH LOAD BLINDER PROTECTION SCHEME

The DOC relay acts as a backup protection for the distance relays located at the remote ends of the 132 kV transmission lines when remote end faults, Fault1 demonstrated in Fig. 4 and Fault2 presented in Fig. 5. During open tie and closed tie configurations, the direction of the fault currents caused by applied faults is observed in the system. When examining this flow, the Backup DOC relay detects reverse direction fault currents.

However, if the reverse current value exceeds the DOC relay current pickup value during normal operation, the DOC relay will detect it as a fault condition. Consequently, in normal network operation where there is no fault condition, the increased reverse current caused by RES surpasses the pickup value of the DOC relay and leads to misoperation in the protection scheme. Therefore, the DOC relay restricts reverse power flow under normal network operation conditions. To overcome the issue of reverse power flow restriction, the DOC function and load blinder function are combined in the DOC with Load Blinder protection scheme which can be seen in Fig. 6 [21]. The Load Blinder function prevents the DOC relay from tripping during reverse load flow under normal operation conditions by applying load blinding. Nonetheless, if there is a fault condition and the fault current exceeds the DOC pickup value, the relay will trip as expected.

Detecting high-resistive faults at the 132 kV remote end can be a challenge. To solve this issue, Negative Sequence (I_2>) and Undervoltage (V<) functions in combination with the DOC with Load Blinder protection scheme is implemented, as illustrated by the logic and conditions presented in Fig. 7 [10], [21].

B. ADAPTIVE PROTECTION FOR DOC WITH LOAD BLINDER SCHEME

The system configuration of RES-integrated distribution networks could change constantly due to various factors such as tap staggering operations, RES generation fluctuations, load variations, switch statuses changes and so on. Therefore, it is necessary to continuously adapt the settings of the DOC and Load Blinder functions, such as the DOC pickup, Load

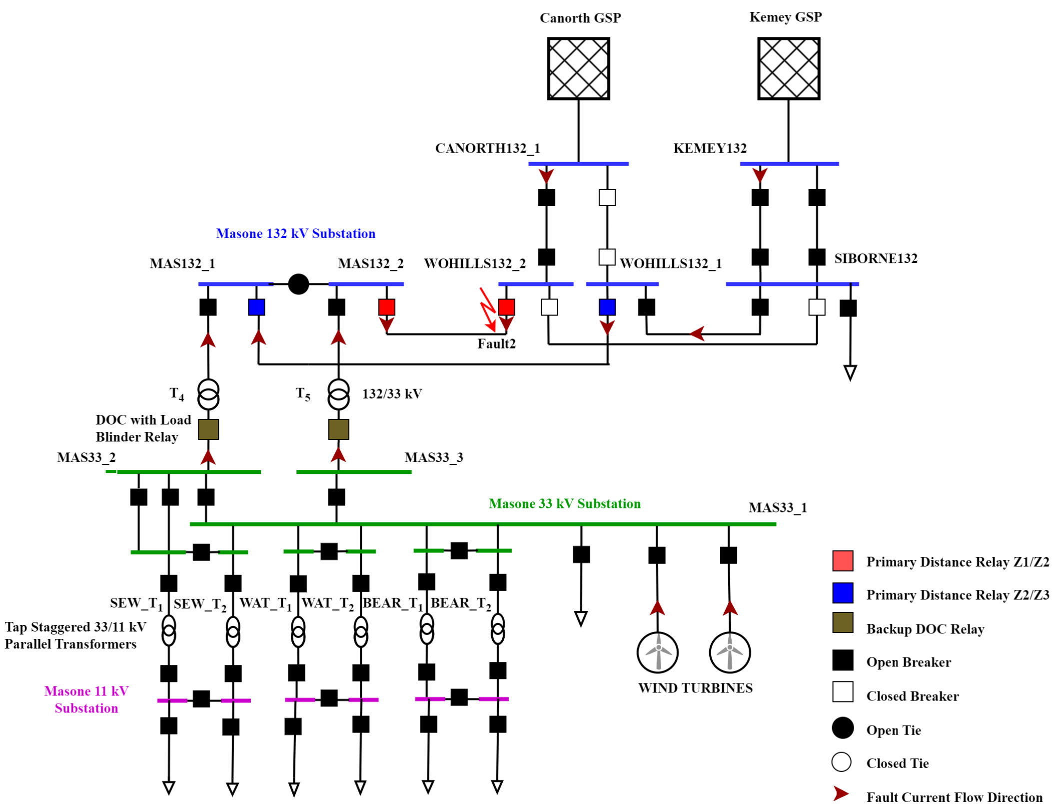

FIGURE 5. Short-circuit current flows during 132 kV remote-end faults in the Masone 132 kV substation closed tie configuration.

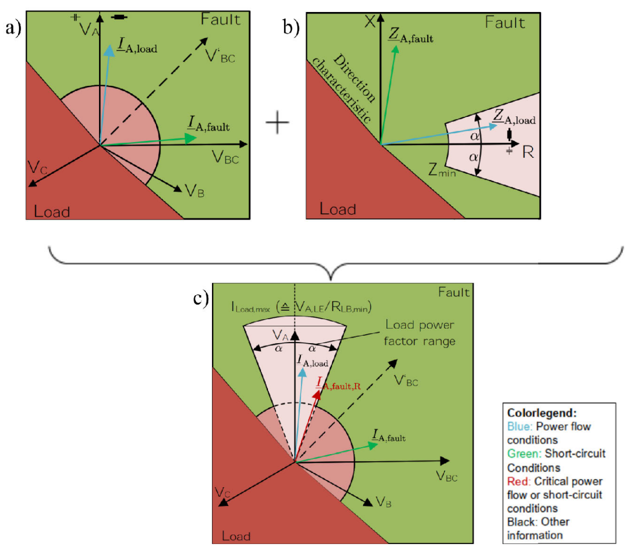

FIGURE 6. DOC with load blinder protection scheme. a) DOC function characteristic in the V-I plane b) Load Blinder function characteristic in the R-X plane. c) Merged DOC and Load Blinder function characteristics in the V-I plane.

Blinder maximum resistance, and Load Blinder maximum angle, to align with the network configuration shown in Fig. 8. Failing to consider changes in network conditions and maintaining constant settings can result in protection system misoperations and malfunctions.

When primary substations in a distribution grid absorb reactive power from the sub-transmission grid to improve bus overvoltage during low demand conditions utilizing tap staggering, there is a potential risk that load blinding protection fails to operate or have a nuisance trip during normal load. In this way, the operation of tap staggering is likely to affect DOC with Load Blinder adaptive protection. The results of the analysis are extensively reviewed in Section V to explore these effects in detail.

IV. NETWORK MODEL, STUDIES AND MACROS

The network model has been created in PSS CAPE by using detailed data from a real demo network. Blue-colored items indicate 132 kV network equipment, green-colored items denote 33 kV equipment, and red-colored items represent 11 kV equipment. Besides, it mainly contains 132 kV grid supply points, 33 kV Wind Generation Area, three pairs of tap staggering applied 33/11 kV transformers and various loads as shown in Fig. 9. The protection model is also included in that network model. In this operation, the grid is fed by a combination of Canorth GSP and Kemey GSP from the 132 kV level and wind generators from the 33 kV level. Depending on varying load and generation scenarios, the

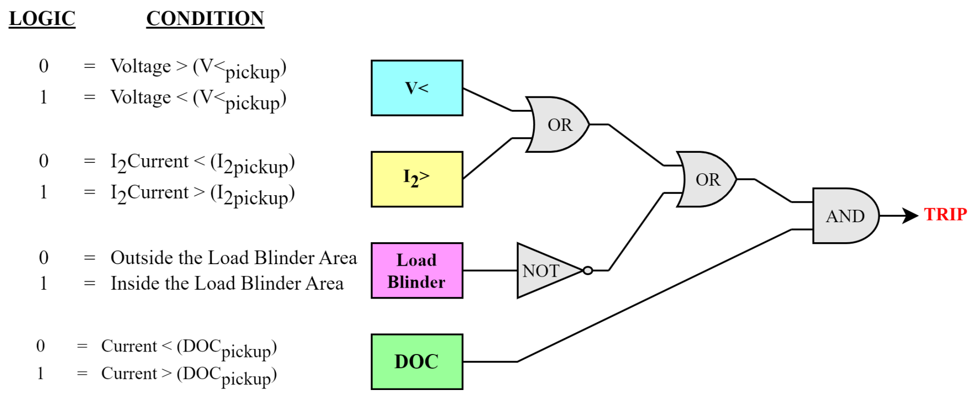

FIGURE 7. Block diagram of the DOC with load blinder protection scheme with undervoltage and negative sequence functions.

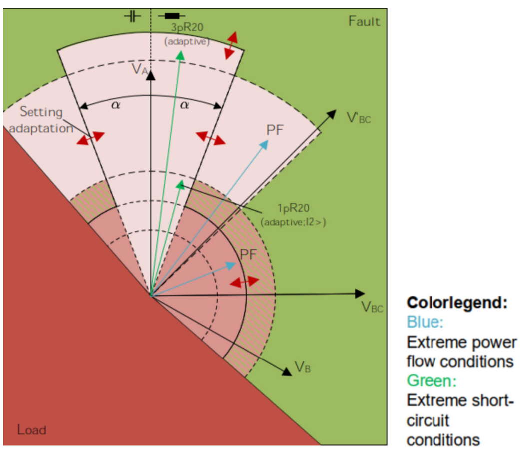

FIGURE 8. V-I characteristic of adaptive DOC with load blinder settings in normal load conditions and short-circuit conditions [21].

direction of power flow shifts either towards the Masone 132 kV transmission system or the Masone 33 kV distribution system. Tap staggering studies performed on the 33/11 kV transformers which are Tap Staggering Transformer Pair 1, 2 and 3. During the studies, tap staggering is applied to 3 transformers together and simultaneously.

A. TAP STAGGERING CONFIGURATION AND MEASUREMENT POINTS IN THE NETWORK

33/11 kV parallel transformers with identical electrical characteristics are modeled with a primary side tap changer, as shown in Fig. 10. The tap changer comprises a total of 17 taps, ranging in voltage from 0.9 pu to 1.1 pu. There is a 1.25% voltage difference between each tap and Tap#9 corresponds to 1 pu voltage. While tap staggering is applied, the minimum tap is set to Tap#5 and maximum tap is set to Tap#13 as the tap changer limits. As an example of the tap stagger application, the tap changer in the WAT_T1 transformer is adjusted up 1 step to Tap#10 while the tap changer in the WAT_T2 transformer is decreased by 1 step to Tap#8. Therefore, a voltage difference is created between two identical parallel transformers and reactive power consumption is realized by ensuring that circulation current flows.

Measurements have been taken from multiple points throughout the network and analyzed, with a focus on the secondary side of the T4 33 kV transformer, the MAS132_1 132 kV busbar, and the 33/11 kV transformers with tap staggering applied.

B. INVESTIGATED CASE STUDIES AND SCENARIOS

This study includes 24 different hourly scenarios. Each scenario varies the generation and load values in the network model according to the hourly wind speed-demand ratios, as shown in Fig. 11. The graphics are created using actual data from the local wind demand/generation data [22]. The two wind turbine generators with a capacity of 90 MVA generate power hourly based on the "Wind Speed Ratio to Peak" coefficients. Additionally, the consumption of loads is adjusted hourly according to the "Demand Ratio to Peak" coefficients.

The generation of 2 wind turbine generators with an installed capacity of 90 MVA modified according to the "Wind Speed Ratio to Peak" coefficients that varies hourly and the consumption of loads is adjusted hourly according to the "Demand Ratio to Peak" coefficients. In addition to the various studies on demand-generation, changing the tap stagger by 5 times per study adds 96 unique studies to the research, bringing the total number of studies to 120.

C. APPLICATION OF TAP STAGGERING AND ADAPTATION PROTECTION MACROS

A special macro has been developed for this study that comprises of two submacros, namely Tap Staggering Macro and Adaptation Protection Macro. These submacros have been designed to automate repetitive analysis steps, as shown in Fig. 12.

As a first analysis, the main macro gets the network model into PSS CAPE and executes the Tap Staggering Macro to obtain tap staggering analysis results based on

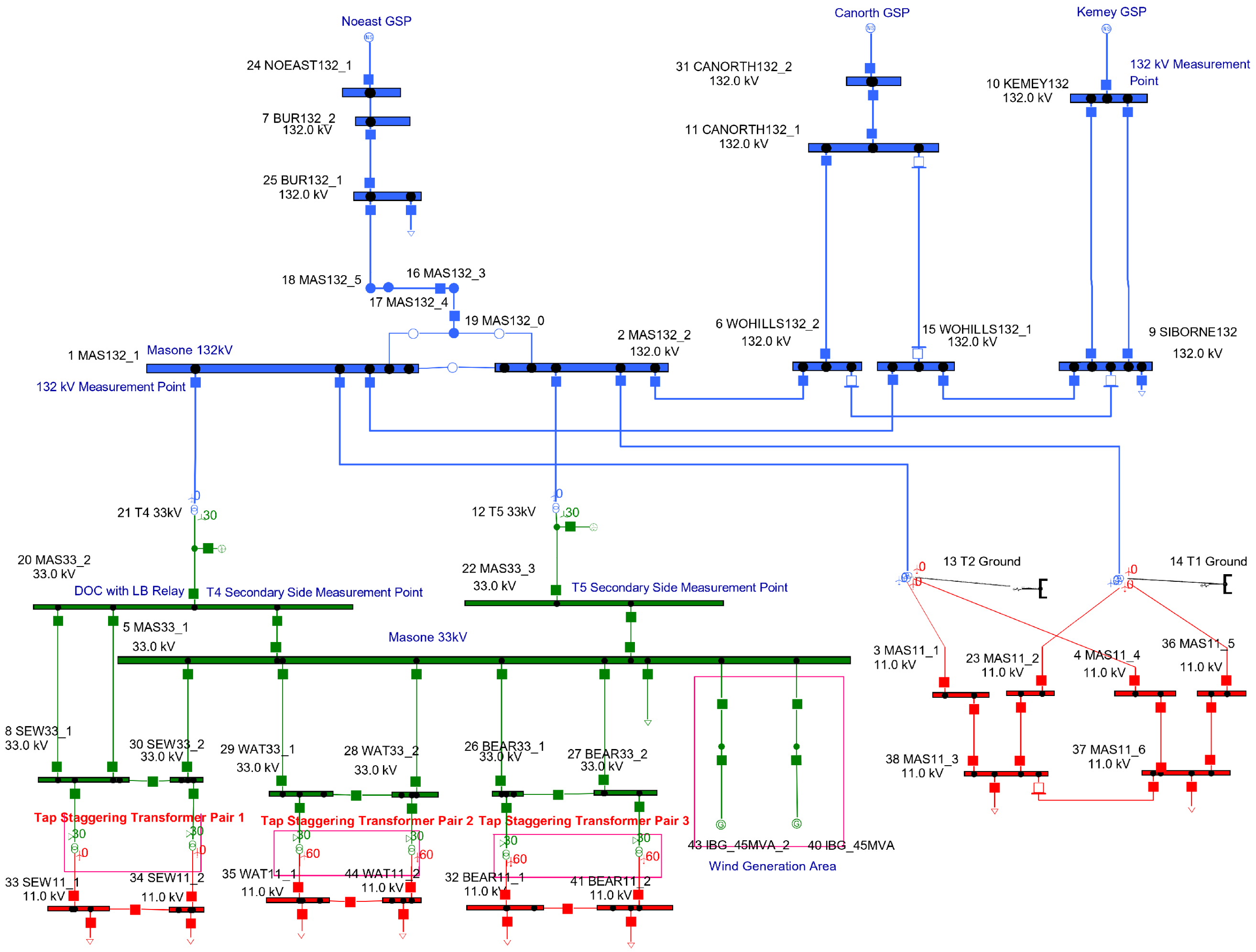

FIGURE 9. Studied Network Model in PSS CAPE.

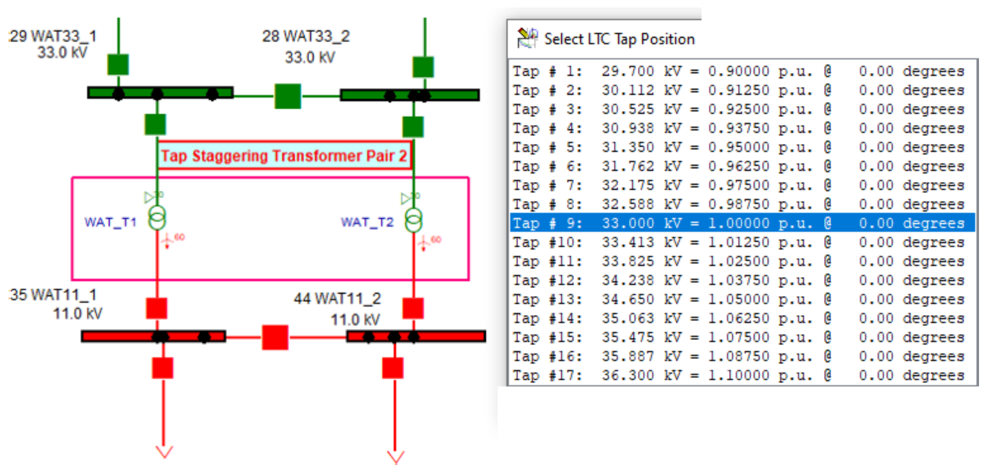

FIGURE 10. Tap staggering applied parallel transformers model and tap positions in PSS CAPE.

the scenarios defined for the study. Initially, the load and generation values in the network model are updated according to the hourly data shown in Fig. 11. Then, a power flow analysis is conducted using the Decoupled Without method on the network model generated for each hour. Finally, the analysis results of tap staggering are obtained as absorbed reactive power, bus voltages, and active power loss on the tap staggered transformers.

As a second analysis, the main macro runs the Adaptation Protection Macro to adapt the $I\!>_{DOC}$, R_{LB}, and α parameters

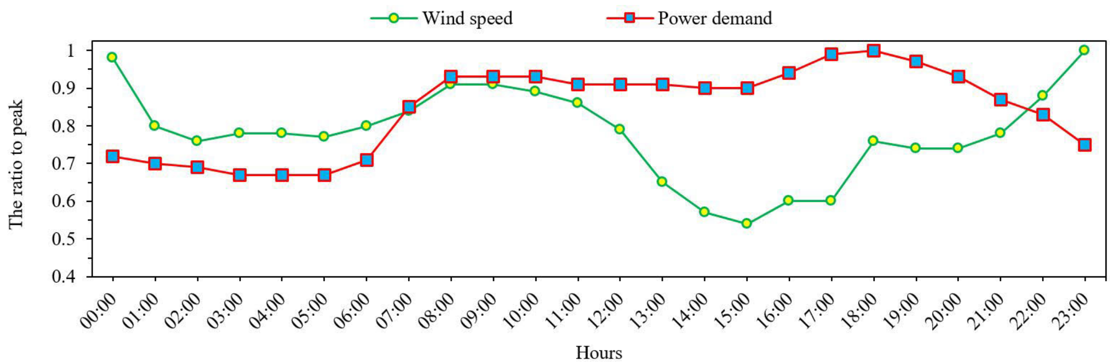

FIGURE 11. **Hourly demand/generation data in 24 hours.**

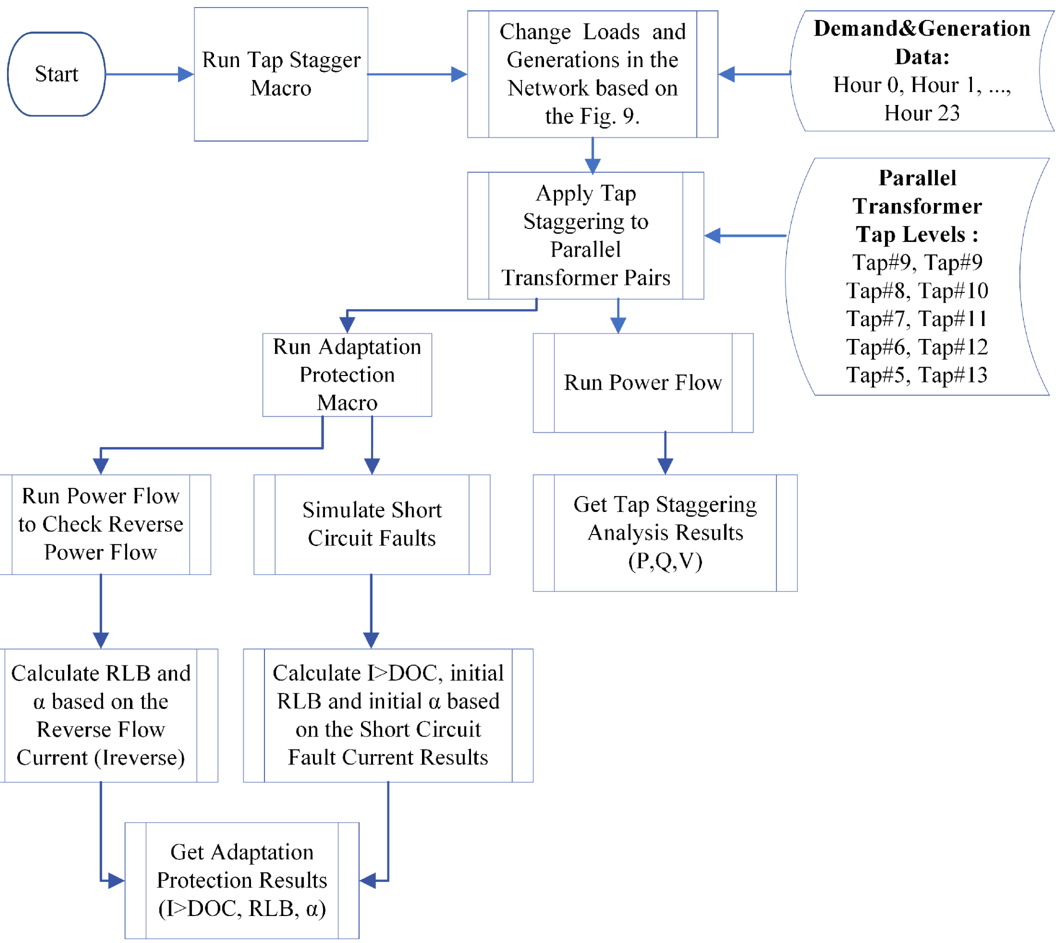

FIGURE 12. **Flow chart of the tap staggering macro.**

of the DOC with the Load Blinder protection scheme according to the last updated network configuration. This submacro performs short circuit analyses by applying three phase with 20 ohm resistive fault and single line ground with 20 ohms resistive fault to the remote end buses, as shown in Fig. 4 and Fig. 5. By the short circuit analysis, minimum values for three phase short circuit current and minimum single phase ground current in the network model are obtained which are measured on the DOC with Load Blinder relay. Then, the value of $I_{>DOC}$ is calculated using the minimum single phase short circuit current value obtained in (14). As an initial maximum Load Blinder current value which is $I_{LBmax,n}$ is calculated by using (15). Primarily, the value of α_n is assigned as the α_{base} value which is 20°.

$$I_{>\mathrm{DOC}} = 0.8\,\min(\text{single phase short circuit current}) \quad (14)$$

$$I_{\mathrm{LBmax,n}} = 0.8\,\min(\text{three phase short circuit current}) \quad (15)$$

$$\alpha_n = \alpha_{\mathrm{base}} = 20^\circ \quad (16)$$

The macro performs power flow analysis with defined load, generation, and network configuration to find the current flowing through DOC with Load Blinder relay, branch active power and branch reactive power. At first, it checks whether $I_{reverse}$ exceeds the $I>_{DOC}$ pickup threshold. If the current through the relay has a reverse direction and exceeds 80% of the calculated $I>_{DOC}$, the macro starts to adapt the R_{LB} parameter. If the condition is not met, the $I_{LBmax,n}$ (15) will be used to calculate R_{LB} parameter and there is no further adaptation is necessary.

To adapt the R_{LB} parameter of the DOC with load blinder protection scheme using the $I_{reverse}$ current, the algorithm shown in Fig. 13 is applied. When 1.2 $I_{reverse} \geq I_{LBmax,n-1}$, thus $I_{LBmax,n}$ is assigned as $1.2I_{reverse}$. If this condition is not met, the $I_{LBmax,n}$ will not be calculated and latest $I_{LBmax,n-1}$ value will be used from the relay. R_{LB} value can be obtained from (17) where V_N is the rated bus voltage.

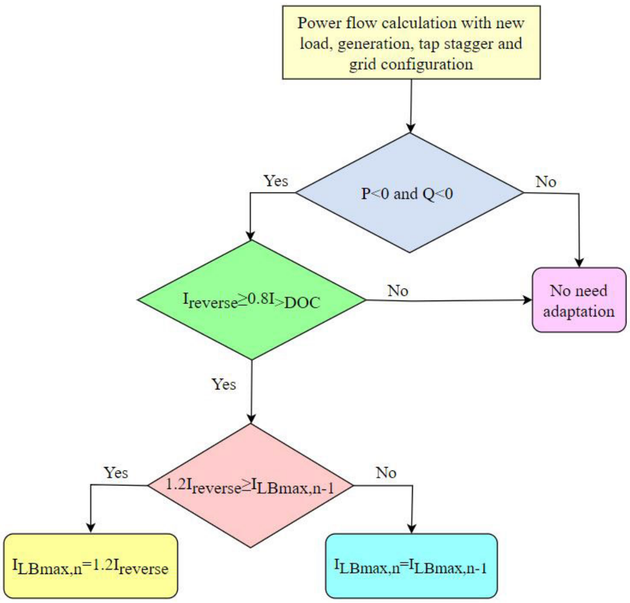

FIGURE 13. R_{LB} **parameter of the DOC with Load Blinder protection scheme adaptation algorithm.**

$$R_{LB} = \frac{V_N}{\sqrt{3} I_{LB\max,n}} \tag{17}$$

For adapting the parameter α_n, the macro initially verifies if there would be a significant change in the power flow angle, as displayed in detail in Fig. 14. First, the previous α_{n-1} value must be lower than the sum of the measured power flow angle ϕ_{PF} and security margin ϕ_{SM} which can be seen in (18). If the condition is not met, the value of α_{n-1} will be assigned as the α_n parameter.

$$|\alpha_{n-1} - \phi_{SM} - \phi_{PF}| > 0 \tag{18}$$

If the condition in (18) is not valid, the latest α_{n-1} will be used as a new α_n. If it is valid, it checks the $\phi_{PF} > \alpha_{base}$ - ϕ_{SM} condition is satisfied to adapt the α_n parameter with

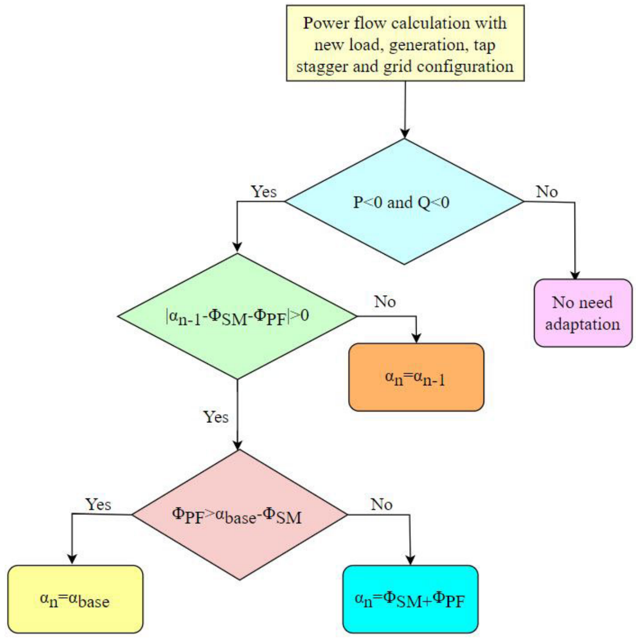

FIGURE 14. α **parameter of the DOC with Load Blinder protection scheme adaptation algorithm.**

the sum of the power flow angle and security margin in (19). Otherwise, the macro returns the α_n to the α_{base} defined in (18). The security margin ϕ_{SM} is defined as 5° to keep α_n wider than ϕ_{PF} to ensure reliable direction detection of power flow seen in the relay [23].

$$\alpha_n = \phi_{SM} + \phi_{PF} \tag{19}$$

All of the previous steps are repeated 5 times, making the parallel transformers tap levels Tap#9, Tap#9; Tap#8, Tap#10; Tap#7, Tap#11; Tap#6, Tap#12 and Tap#5, Tap#13 with the application of tap staggering for each hour studies in 24 hours. Since 24 different studies are repeated for each hour, 120 different study results are collected. At the end of the macros, thanks to the developed Python script all the data is automatically exported into tables and the necessary graphs are created.

V. ANALYSIS RESULTS

The analysis results section presents all results obtained from conducted studies. In the tap staggering analysis results, the total reactive power consumption is presented. Then, it is shown how this absorption affects the bus voltages in the network system. To investigate the active losses in the transformers, the amount of active power loss in the parallel transformers caused by tap staggering application has been studied. In conlusion, the effects of the tap staggering application on the DOC with load blinder adaptation protection scheme have been studied and the analysis results section is completed.

A. TOTAL REACTIVE POWER ABSORPTION

Figure 15 displays the individual impact of one parallel transformer pair, SEW_T1 and SEW_T2, on the system at

33/11 kV. It has been observed that only one pair of parallel transformers consumes about 1 MVAr reactive power in 24 hours in each study.

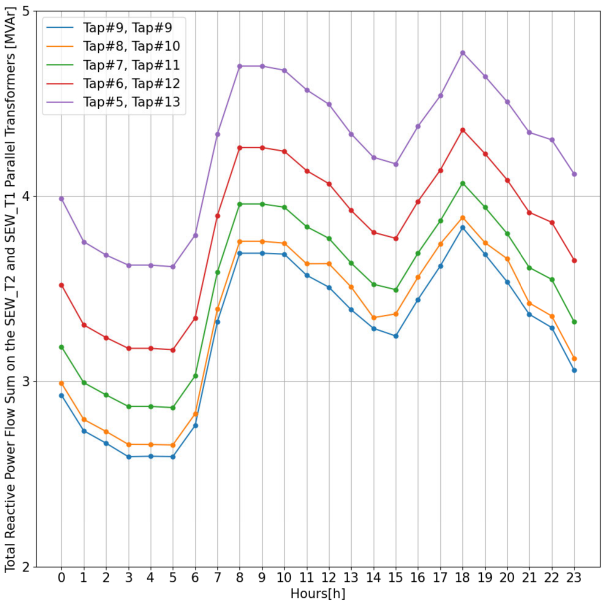

FIGURE 15. Total sum of reactive power flow on the SEW_T1 and SEW_T2 parallel transformers over a 24-hour period.

The flow of reactive power increases gradually with an increase in the tap level difference between parallel transformers. It has been observed that the reactive power consumption between parallel transformers at Tap#6, Tap#12 and and at Tap#5, Tap#13 is 465 kVAr, which is much higher than the reactive power consumption between parallel transformers at Tap#9, Tap#9 and at Tap#8, Tap#10 which is 65 kVAr.

Tap staggering is applied to the three parallel transformer pairs in the analyzed network system. To understand the aggregated reactive power absorption effect of the tap staggering application on the network system, the sum of the reactive power flow is measured at the T4 and T5 transformers located between the 132 kV and 33 kV buses, as shown in Fig. 16. The negative MVAr values indicate reverse power flow from the 33 kV substation to the 132 kV substation. The tap staggering application resulted in a total reactive power absorption of 2.36 MVAr across all 24-hour demand/generation studies in the network system.

B. TAP STAGGERING EFFECTS ON THE BUS VOLTAGES

Depending on the regulations, the voltage levels on the network system must be within specific limits such as ±5%. During the 0th and 23rd hour scenarios at the MAS132_1 bus, the voltage level exceeds the 1.05 pu level, requiring a decrease in the voltage level. When the tap staggering is applied and the tap level differences are increased, the voltage level on the MAS132_1 bus is brought to safe limits, which are between 0.95 and 1.05 as can be seen in Fig. 17. When

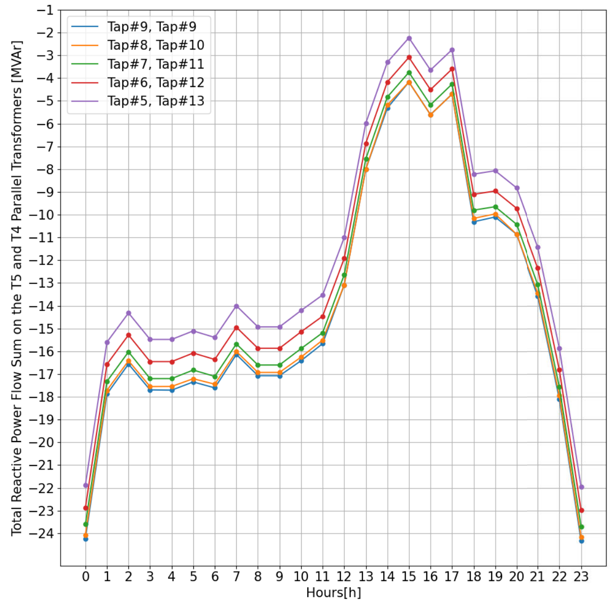

FIGURE 16. Total sum of reactive power flow on the T5 and T4 parallel transformers in 24 hours.

the results of all the scenarios shown in Fig. 18 are examined, it can be seen that the voltage level of the T4 33 kV bus can also be reduced by using tap staggering.

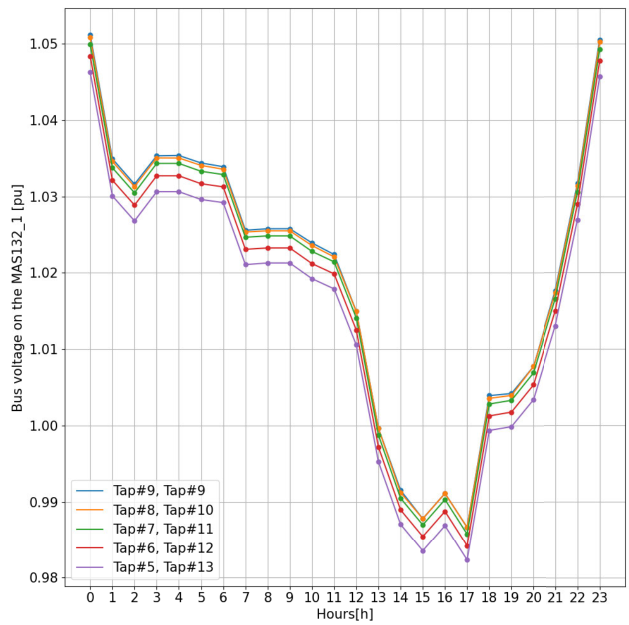

FIGURE 17. Voltage changes on the MAS132_1 bus in 24 Hours.

The bus voltage measurements for T4, T5, MAS132_1, KEMEY, SEW_T1, WAT_T1, and BEAR_T1 at different tap staggering levels are presented in Table 1. In the beginning, the voltage level exceeds the 1.05 pu upper limit on the T4, T5, SEW_T1, WAT_T1, and BEAR_T1 buses. As a result of the gradually applied tap staggering, it is concluded that the voltage levels on all buses have decreased. In case the tap levels of the parallel transformers are Tap#5, Tap#13;

the busbar voltages are brought back to the allowed voltage limits.

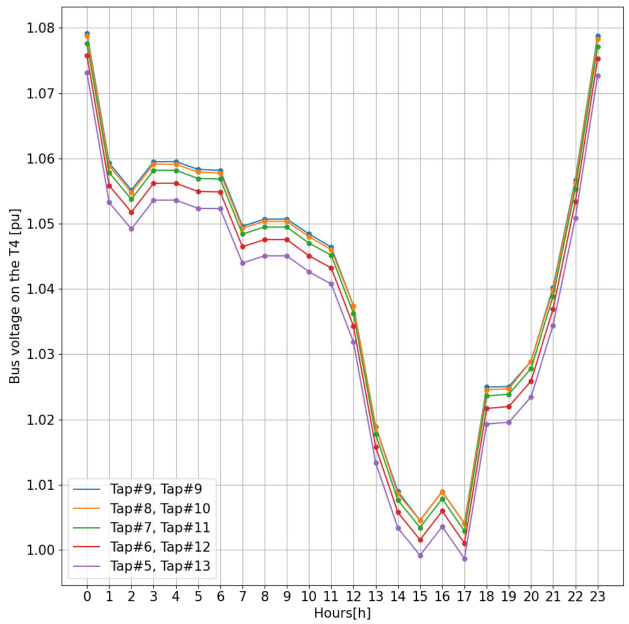

FIGURE 18. **Voltage changes on the T4 33 kV bus in 24 Hours.**

C. ACTIVE POWER LOSS ON THE TAP STAGGERING APPLIED TRANSFORMERS

The voltage difference between the parallel transformers creates a circulating current that causes power losses in the transformers. In this study, the active power loss on transformers is calculated during the tap staggering application for each scenario.

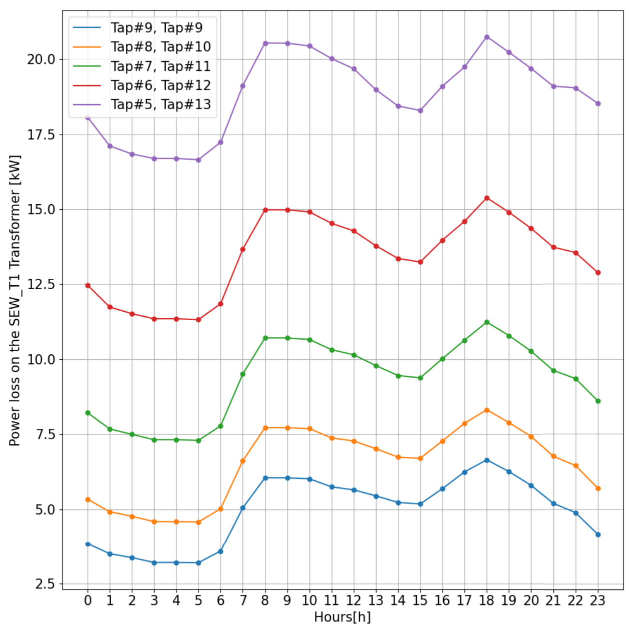

FIGURE 19. **Power loss on the SEW_T1 transformer in 24 Hours.**

In the beginning, active power loss on the SEW_T1 transformer was only 5.34 kW in Hour 0. When the parallel transformers tap level is set to Tap#5, Tap#13 that means the tap difference between parallel transformers is 8 and the highest tap difference level in this study, active power loss increases up to 18 kW. The result of the analysis, it has only 12.66 kW power loss when the tap levels are changed from Tap#9, Tap#9 to Tap#5, Tap#13.

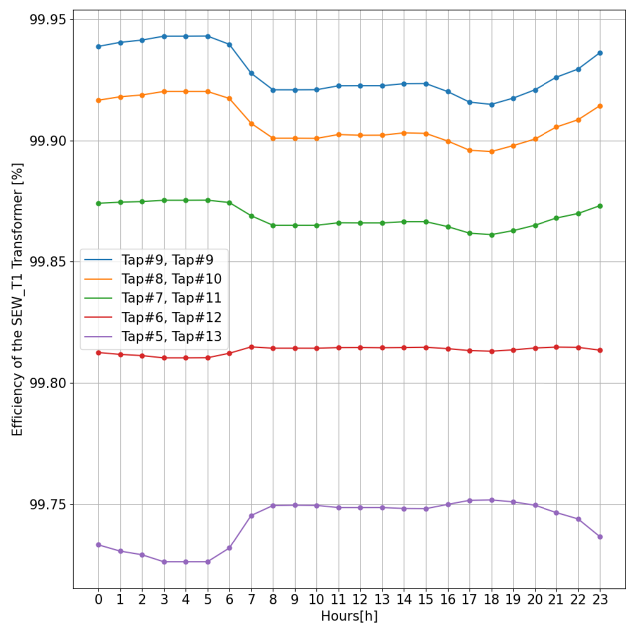

FIGURE 20. **Efficiency of the SEW_T1 transformer in 24 Hours.**

When the transformer efficiency with varying levels of tap stagger are analyzed in Fig. 20, while the efficiency is 99.9 at Tap#9, Tap#9, the efficiency drops to 99.72 at the maximum level when Tap#5, Tap#13 is applied. According to EU Regulations, the minimum permitted Tier 2 minimum efficiency for a 40 MVA transformer is 99.724%, while Tier 1 minimum efficiency is 99.684%. All scenarios in Fig. 19 and Fig. 20 prove that active power loss increases when tap staggering is applied but these power losses stay at reasonable levels based on the efficiency limits [24].

D. TAP STAGGERING EFFECTS ON THE DOC WITH LOAD BLINDER PROTECTION SCHEME ADAPTATION PROTECTION

The application of tap staggering causes various changes in network parameters such as $I_{reverse}$ current and remote-end short circuit fault currents that affect the DOC with the Load Blinder protection scheme. As an initial step, the results are obtained without the application of tap staggering (parallel transformers tap at Tap#9, Tap#9). Then, by applying tap staggering to 3 pairs of parallel transformers in the 33/11 kV network, the results for 4 different studies have been obtained, such as parallel transformer tap levels at Tap#9, Tap#9; Tap#8, Tap#10; Tap#7, Tap#11; Tap#6, Tap#12 and

TABLE 1. Bus voltage changes on the different buses depend on the various tap staggering applications in Hour 2.

Parallel Transformer Tap Levels	T4	T5	MAS132_1	KEMEY	SEW_T1	WAT_T1	BEAR_T1
Tap#9, Tap#9	1.055	1.055	1.031	1.023	1.055	1.055	1.054
Tap#8, Tap#10	1.054	1.055	1.031	1.023	1.054	1.055	1.053
Tap#7, Tap#11	1.053	1.054	1.030	1.022	1.053	1.054	1.052
Tap#6, Tap#12	1.051	1.052	1.028	1.020	1.051	1.052	1.050
Tap#5, Tap#13	1.049	1.049	1.026	1.018	1.049	1.049	1.048

Tap#5, Tap#13. As can be seen in Table 2, while the tap difference between parallel transformers increases in tap staggering application; reverse current, and active-reactive power values on the T4 transformer secondary side gradually decrease based on the Hour 0.

As seen in Table 2, when the tap difference between the parallel transformers is increased while applying tap staggering, the reverse current and active-reactive power values on the secondary side of the T4 transformer gradually decrease in the Hour 0 scenario.

The initial pickup value of the DOC function ($I>_{DOC}$ Pickup) has been set to 780 A in the DOC with the Load Blinder scheme. The $I>_{DOC}$ Pickup value has adapted to 791 in a network operation without tap staggering. Applying tap staggering with varying tap differences reduces the minimum single-phase short circuit current in the network due to the absorption of reactive power, as demonstrated in these studies.

Thus, the adaptation algorithm calculates the $I>_{DOC}$ Pickup value as 785 A by using minimum short-circuit fault current that is measured from remote ends during tap staggering application, with taps at Tap#5, Tap#13 which shows an 8 tap difference between the parallel transformers.

The initial setting for the resistive reach value of the Load Blinder function $R_{LB,n-1}$ has set to 63.5 ohms in the DOC with the Load Blinder scheme. After the adaptation, the $R_{LB,n-1}$ value adapted to 24.99 ohm due to a variation in the $I_{reverse}$ during Hour 0 of the study. Since the former I_{LBmax} value is lower than $I_{reverse}$, it is necessary to adapt the resistive reach value in scenarios where tap staggering is applied incrementally. For this reason, the R_{LB} value is adapted by the calculation according to (17). The α of the Load Blinder function is calculated according to the $I_{reverse}$ current. It is initially set at 43 degrees, then adapted to 23.3 degrees when tap staggering is not applied. After tap staggering started to be applied, the power factor angle decreased depending on the reactive power absorption by tap staggering transformers. Therefore, as the transformer tap difference applied for tap staggering increases, the α gradually decreases. It is seen that the tap staggering application directly affects the α value in Fig. 21.

Four different hours are selected from the studied scenarios and the adapted DOC with Load Blinder parameters are provided in Table 4 for comparison. In Hour 0, the level of generation nears its maximum capacity while the consumption is at its lowest level. During Hour 4, the generation is

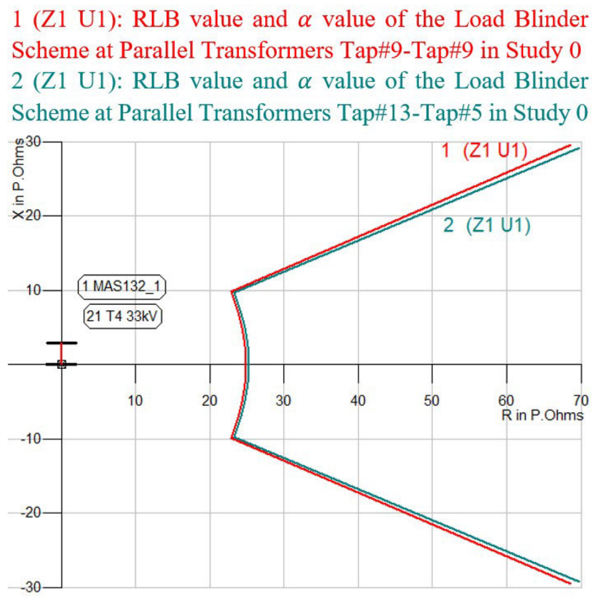

FIGURE 21. Change of α and R_{LB} of the DOC with Load Blinder scheme when parallel transformer tap levels are changed from Tap#9, Tap#9 to Tap#5, Tap#13.

at a medium level while the consumption continues to stay at the lowest level. By Hour 15, the generation dips to the lowest level of the day while the consumption increases and nears its maximum level. Finally, in Hour 18, the generation returns to a medium level while the consumption reaches its peak. When analyzing the adapted parameters in four different scenarios throughout the day, it is observed that the protection parameters are changing. Specifically, $I>_{DOC}$ can vary from 650 to 791 A, R_{LB} can vary from 24.99 to 16.63 ohms, and α can vary from 23.3 to 20 degrees on the same day. These parameters must be adapted in response to changes in demand/generation during the 24-hour period and different tap staggering levels.

In terms of power quality, the power factor is 0.9495 before the tap staggering is applied, the power factor becomes 0.9525 when the tap staggering applied as Tap#5, Tap#13 which is the highest tap level, as can be seen in Table 2. This power factor variation is a small amount of change, and the power quality is not affected by tap staggering application. The power factor values in Table 4, which vary depending on the different demand/generation scenarios during the day and

TABLE 2. Measured values on the secondary side of the T4 transformer at different tap stagger levels in Hour 0.

Parallel Transformer Tap Levels	Ireverse (A)	Branch P (MW)	Branch Q (MVAr)	Power Factor (cosϕ)	Iscmin (A)	I3pmin (A)
Tap#9, Tap#9	635.1	37.20	12.29	0.9495	988.90	1496.2
Tap#8, Tap#10	634.8	37.17	12.26	0.9497	988.40	1495.7
Tap#7, Tap#11	633.8	37.09	12.16	0.9502	986.85	1494.2
Tap#6, Tap#12	632.3	36.98	12.00	0.9512	984.31	1491.7
Tap#5, Tap#13	630.1	36.81	11.76	0.9525	980.75	1488.2

TABLE 3. Adapted values of DOC with Load Blinder Relay are located on the T4 transformer's secondary side at various tap staggering levels during Hour 0.

Parallel Transformer Tap Levels	I>DOCn-1 (A)	Adapted I>DOC (A)	R>LBn-1 (Ohm)	Adapted R>LB (Ohm)	αn-1 (Deg)	Adapted α (Deg)
Tap#9, Tap#9	780	791	63.5	24.99	43	23.3
Tap#8, Tap#10	780	791	63.5	25.01	43	23.3
Tap#7, Tap#11	780	789	63.5	25.05	43	23.2
Tap#6, Tap#12	780	787	63.5	25.11	43	23.0
Tap#5, Tap#13	780	785	63.5	25.19	43	22.7

TABLE 4. Adapted values of DOC with Load Blinder Protection Scheme in Hour 0, Hour 4, Hour 15 and Hour 18.

Study Number - Parallel Transformer Tap Levels	Iscmin (A)	Adapted I>DOC (A)	Ireverse (A)	Adapted R>LB (Ohm)	Power Factor (cosϕ)	ϕPF (Deg)	Adapted α (Deg)
Hour 0 - Tap#9, Tap#9	989	791	635	24.99	0.9495	18.3	23.3
Hour 0 - Tap#5, Tap#13	981	785	630	25.19	0.9525	17.7	22.7
Hour 4 - Tap#9, Tap#9	932	746	581	16.63	0.9555	17.15	20
Hour 4 - Tap#5, Tap#13	924	739	576	16.73	0.9588	16.51	20
Hour 15 - Tap#9, Tap#9	820	657	475	18.37	0.9684	14.45	20
Hour 15 - Tap#5, Tap#13	813	650	470	18.47	0.9717	13.66	20
Hour 18 - Tap#9, Tap#9	884	707	533	17.41	0.9602	16.22	20
Hour 18 - Tap#5, Tap#13	876	701	528	17.51	0.9633	15.58	20

the tap staggering application show slight differences as well and support the derived conclusion.

After the tap staggering analysis, the parameters $I>_{DOC}$, R_{LB}, and α for the DOC with Load Blinder protection scheme have been altered and require adaptation. Consequently, the protection system will operate reliably, and the power generated by the RESs can be transmitted to the transmission system more efficiently without any restriction by the protection system and tap staggering operation.

VI. CONCLUSION

According to the study results obtained by applying the Tap Staggering Macro, in all scenarios, there is reactive power absorption in the identical parallel transformers because of the circulation current flowing between them with the tap staggering application. For this reason, all busbar voltages in the network decrease proportionally with the increase in reactive power consumption of the tap staggered parallel transformers. Thus, the overvoltage problem in the transmission network during low demand periods is eliminated. Considering the effect of the tap staggering Volt/VAr control method on the protection system, it is concluded that the DOC with the Load Blinder protection scheme is affected in all scenarios due to the tap stagger application changes the short circuit currents and active-reactive powers measured on the Load Blinder Relay. Using the Adaptation Protection Macro; the $I>_{DOC}$ pickup, R_{LB} and α parameters within the protection scheme have been adapted to the changing demand/generation scenarios based on RESs. Therefore, the protection system operates reliably with an adapted protection scheme, enabling more efficient delivery of power generated by RESs to the transmission system without any restrictions from the the protection scheme or tap staggering operation. In future studies, tap staggering can be applied to transformers in more substations and the effects on the network can be examined using larger systems. Besides, the entire protection system in the network can be modeled and the coordination of the DOC adapted with the Load Blinder scheme and other protection elements can be studied by accounting for the tap staggering effect.

REFERENCES

[1] *Climate Change 2014 Synthesis Report Summary for Policymakers*, IPCC, Geneva, Switzerland, 2014.

[2] *Energy Technology Perspectives 2020*, Int. Energy Agency, Paris, France, 2020.

[3] B. P. Bhattarai, B. Bak-Jensen, S. Chaudhary, and J. R. Pillai, "An adaptive overcurrent protection in smart distribution grid," in *Proc. IEEE Eindhoven PowerTech*, Eindhoven, The Netherlands, Jun. 2015, pp. 1–6, doi: 10.1109/PTC.2015.7232310.

[4] L. Chen, H. Li, V. Turnham, and S. Brooke, "Distribution network supports for reactive power management in transmission systems," *IEEE PES Innov. Smart Grid Technol., Eur.*, Istanbul, Turkey, 2014, pp. 1–6, doi: 10.1109/ISGTEurope.2014.7028922.

[5] L. Chen, H. Y. Li, S. Cox, and K. Bailey, "Ancillary service for transmission systems by tap stagger operation in distribution networks," *IEEE Trans. Power Del.*, vol. 31, no. 4, pp. 1701–1709, Aug. 2016, doi: 10.1109/TPWRD.2015.2504599.

[6] Z. Gao, H. Li, and L. Chen, "Optimized voltage-led customer load active service using genetic algorithm in distribution networks," *IEEE Access*, vol. 10, pp. 22844–22853, 2022, doi: 10.1109/ACCESS.2022.3153111.

[7] Electricity North West Ltd. *U.K. CLASS Technology*. Accessed: Mar. 1, 2023. [Online]. Available: https://www.enwl.co.uk/go-netzero/innovation/key-projects/class/learning-and-key-documents/classtechnology/

[8] A. O. Rousis, Y. Pipelzadeh, B. Chaudhuri, T. Green, and G. Strbac, "Voltage support from distribution level resources in South-East England," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Portland, OR, USA, Aug. 2018, pp. 1–5, doi: 10.1109/PESGM.2018.8586175.

[9] *U.K. Power Networks*. Accessed: Mar. 1, 2023. [Online]. Available: https://innovation.ukpowernetworks.co.uk/wpcontent/uploads/2019/05/Novel-Protection-Relay-Trial-Report.pdf

[10] A. Al-Riyami, K. Burt, G. Manhangwe, P. Pretlove, and S. Georgiopoulos, "An investigation into alternatives to directional overcurrent protection on grid transformers to improve the network capacity to accommodate reverse power flow," in *Proc. 12th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Copenhagen, Denmark, Mar. 2014, pp. 1–6, doi: 10.1049/cp.2014.0159.

[11] M. Purlu and B. E. Turkay, "Optimal allocation of renewable distributed generations using heuristic methods to minimize annual energy losses and voltage deviation index," *IEEE Access*, vol. 10, pp. 21455–21474, 2022, doi: 10.1109/ACCESS.2022.3153042.

[12] H. Mataifa, S. Krishnamurthy, and C. Kriger, "Volt/VAR optimization: A survey of classical and heuristic optimization methods," *IEEE Access*, vol. 10, pp. 13379–13399, 2022, doi: 10.1109/ACCESS.2022.3146366.

[13] B. M. Weedy, B. J. Cory, N. Jenkins, J. B. Ekanayake, and G. Strbac, *Electric Power Systems*, 5th ed. London, U.K.: Wiley, 2012, pp. 180–183.

[14] J. Dixon, L. Moran, J. Rodriguez, and R. Domke, "Reactive power compensation technologies: State-of-the-art review," *Proc. IEEE*, vol. 93, no. 12, pp. 2144–2164, Dec. 2005, doi: 10.1109/JPROC.2005.859937.

[15] K. Mahmoud, M. M. Hussein, M. Abdel-Nasser, and M. Lehtonen, "Optimal voltage control in distribution systems with intermittent PV using multiobjective Grey-Wolf-Lévy optimizer," *IEEE Syst. J.*, vol. 14, no. 1, pp. 760–770, Mar. 2020, doi: 10.1109/JSYST.2019.2931829.

[16] F. B. Alhasawi and J. V. Milanovic, "Techno-economic contribution of FACTS devices to the operation of power systems with high level of wind power integration," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1414–1421, Aug. 2012, doi: 10.1109/TPWRS.2012.2186594.

[17] M. L. Chen. (Sep. 18, 2015) *Network Modelling and Reactive Power Absorbability Analysis*. Work Package 2-Part B. Accessed: Feb. 17, 2023. [Online]. Available: https://www.enwl.co.uk/globalassets/innovation/class/class-documents/reactive-power-absorption-capability-assessment-final-report.pdf

[18] L. Chen, "Distribution network supports for transmission system reactive power management," Ph.D. dissertation, Elect. Electron. Eng., Univ. Manchester, Manchester, U.K., 2015.

[19] Y. Guo, "Capability assessment of VAr support and demand response to transmission network using flexible tap changing techniques in distribution networks," Ph.D. dissertation, Elect. Electron. Eng., Univ. Manchester, Manchester, U.K., 2017.

[20] A. Wixon, K. Venkataraman, P. Newman, and K. Maleka, "Load blinding stabilisation for DOC relays subjected to reverse load flow," in *Proc. 12th IET Int. Conf. Develop. Power Syst. Protection (DPSP)*, Copenhagen, Denmark, Mar. 2014, pp. 1–9, doi: 10.1049/cp.2014.0077.

[21] R. Ganjavi, C. Scoble, S. Hann, H. Kasap, R. Dantas, J. Meyer, N. Bhadra, B. Yazadzhiyan, and J. Jaeger, "On-line and adaptive protection system to resolve load blinding protection scheme limits in networks with highly integrated DERs," in *Proc. 27th Int. Conf. Electr. Distrib. (CIRED)*, Italy, 2023, pp. 1778–1782, doi: 10.1049/icp.2023.1014.

[22] *GRIDWATCH*. Accessed: Mar. 22, 2023. [Online]. Available: https://www.gridwatch.templar.co.uk/

[23] *SIPROTEC 5. Distance Protection, Line Differential Protection, and Overcurrent Protection for 3-Pole Tripping, C53000-G5040 C010-M*, Siemens, Nuremberg, Germany, 2023.

[24] Official Journal of the European Union. (May 21, 2014). *Commission Regulation (EU) No 548/2014*. L152. Accessed: Oct. 24, 2023. [Online]. Available: https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=uriserv:OJ.L_.2014.152.01.0001.01.ENG

HAKAN KASAP received the B.S. degree in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 2019, where he is currently pursuing the M.S. degree. In 2019, he joined Siemens, Turkey, where he is working in the power system software research and development and power system consulting areas. He is also a specialist in power system software development, power system modeling and analysis, and protection and coordination. He has more than five years of experience in the development of power system software and consulting with a focus on protection studies for customers in transmission and distribution, power generation, and industry sectors. His research interests include power system software development, power system protection, distributed generation, renewable energy, storage systems, and electric vehicles.

MIKAIL PURLU received the bachelor's degree in electrical and electronics engineering from Sivas Cumhuriyet University, Sivas, Turkey, in 2013, and the master's and Ph.D. degrees in electrical engineering from Istanbul Technical University, Istanbul, Turkey, in 2017 and 2022, respectively.

From 2014 to 2022, he was a Research Assistant with Istanbul Technical University. He is currently an Assistant Professor with the Department of Electrical and Electronic Engineering, Sivas Cumhuriyet University. His research interests include distributed generation, power system optimization, renewable energy, and smart grids. He is a member of the CIGRE, Turkey, and a Technical Writer Editor of the *Turkish Journal of Electrical Power and Energy Systems* (TEPES).

BELGIN EMRE TURKAY was born in Istanbul, Turkey. She received the B.S., M.S., and Ph.D. degrees in electrical engineering from Istanbul Technical University (ITU), Istanbul.

She is currently a Professor and the Head of the Department of Electrical Engineering, ITU. Her research interests include power quality, renewable energy, smart grids, and power system resilience. She is a member of the CIGRE, Turkey, and an Editor of the *Turkish Journal of Electrical Power and Energy Systems* (TEPES).

REZA GANJAVI (Senior Member, IEEE) received the Ph.D. degree in power system protection from the Otto von Guericke University of Magdeburg, Germany. In 2001, he joined Siemens PTI, Germany, where he is working in the field of protection studies. He has more than 24 years of experience in power system consulting and the development of innovative software solutions with a focus on protection studies and study management for customers in T&D, power generation, industry, and electric rail sectors. In 2023, he joined Siemens AG as the Team Lead to contribute more to large-scale projects and solutions for decarbonization and sustainability. He is a specialist in protection system design, coordination, and functional security assessment.