Performance of Solid-State Transformers on Voltage Regulation of Active Distribution Networks

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***Abstract*—This paper deals with the recently emerging technology of solid-state transformers (SSTs), focusing on the technical benefits provided towards the optimal network operation. More specifically, the contribution of the SST to the well-known Volt/Var optimization problem is examined in terms of voltage regulation, minimization of network losses, and reduction of the computational burden. For this purpose, the mathematical formulation of the optimization problem is properly modified to incorporate the distinctive characteristics of SST. Deterministic and probabilistic simulations are performed on an extended radial medium-voltage network with high penetration of distributed generation to demonstrate the improved performance of SST against conventional transformer.**

***Index Terms*—Loss minimization, solid-state transformer, voltage control, volt/var optimization.**

I. Introduction

Conventional power transformers are essential elements for the safe and reliable network operation, delivering electrical energy to end-users within pre-specified power quality (PQ) standards [1]. Transformers are also used to regulate network voltages within certain limits by varying their transformation ratio in discrete steps [2]. This is implemented by either on-load or off-load tap changers, which are generally installed in high-voltage/medium-voltage (HV/MV) or medium-voltage/low-voltage (MV/LV) transformers, respectively.

The rapid deployment of distributed generation (DG) over the last years has led to the transition from passive to active distribution networks, causing a series of PQ violations [3]. To address these issues, the paradigm of smart grid is proposed [4]. This is a conceptual framework for the future distribution grids, which includes the following distinctive features: Increased observability and monitoring of the network, data management, and development of new control strategies to mitigate PQ violations. Therefore, there is a strong need for transformers to provide additional capabilities in order to actively participate in the smart grid concept.

Solid-state transformers (SSTs) have recently been developed as an alternative to conventional transformers [5]–[7]. This type of transformer is based on power electronics and offers several new features, such as harmonic compensation, power factor correction, voltage sag compensation, etc. Furthermore, SST presents reduced size and weight compared to conventional transformer, due to the utilization of a high frequency transformer.

In the literature, the main research efforts focus on the design, control, and actual implementation of SST [8]–[10], without investigating the impact of its additional capabilities on network operation. This paper attempts to fill this gap by evaluating the technical benefits that SST provides at the network operation from a power systems point of view. In particular, the contribution of SST to the Volt/Var optimization problem is investigated by means of regulating network voltages and minimizing network losses. This is done, in a way that reduces computational burden, by modifying the mathematical formulation of the Volt/Var optimization problem to model the new features of SST. Furthermore, to thoroughly evaluate the SST performance on network operation, time-series deterministic and probabilistic simulations are performed on an extended radial MV network.

Following this introduction, the remaining of the paper is organized as follows: Section II presents an overview of the conceptual design of SST, while the Volt/Var optimization problem and the corresponding modifications are analytically described in Section III. Results from time-series deterministic and probabilistic simulations are presented and discussed in Section IV. Finally, Section V concludes the paper.

II. Conceptual Design of SST

According to the literature, the most widespread SST design is depicted in Fig. 1 consisting of 5 operation stages. These stages are numbered assuming the step down operation of SST. The first two stages involve the frequency transformation of voltage at HV side from the base network frequency of 50 Hz to a higher frequency, which can be of order of kHz [6]. This can be implemented by an ac/dc/ac converter connected to the HV side, as shown in Fig. 1. Afterward, the third stage includes the voltage magnitude transformation to a lower voltage level by employing a high frequency transformer. This type of transformer has reduced size and weight against the conventional power transformer, since it operates at high frequency. Finally, an ac/dc/ac converter is

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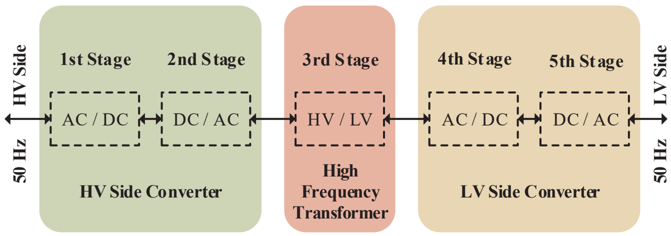

Fig. 1. Conceptual design of SST.

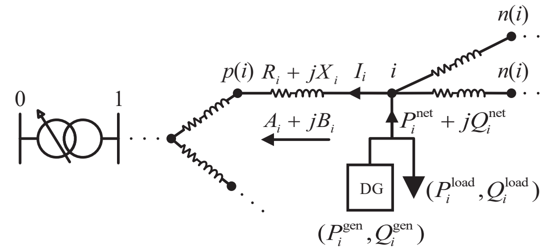

Fig. 2. A typical radial distribution network.

connected to LV side of the high frequency transformer to carry out the last two stages, i.e., restoring the frequency to the base network value of 50 Hz. It is worth mentioning that SST allows a bidirectional power flow similar to the conventional transformer.

III. Volt/Var Optimization Problem

In this Section, the conventional Volt/Var control strategy is analytically presented, while its inherent drawbacks are effectively addressed by introducing the SST operation.

A. Conventional Approach

The Volt/Var control is generally an optimization problem aiming to the effective voltage regulation with minimum active power losses. In distribution networks with high DG penetration, this control strategy mainly utilizes two different types of network elements, namely the DG units and the transformer tap changer. The former are used as controllable reactive power sources, while the latter is employed as a traditional means to regulate network voltages. As a result, the Volt/Var control is formulated for a certain control period as a mixed-integer nonlinear optimization, according to (1)-(11). To facilitate the reading, the variables of the following equations are graphically represented in the typical radial network of Fig. 2.

$$\min \sum_{i\in N} P_{\mathrm{loss},i} \tag{1}$$

subject to

$$P_{\mathrm{loss},i} = R_i(A_i^2+B_i^2)/V_i^2 \quad \forall i\in N \tag{2}$$

$$Q_{\mathrm{loss},i} = X_i(A_i^2+B_i^2)/V_i^2 \quad \forall i\in N \tag{3}$$

$$A_i = \sum_{k\in N_{\mathrm{d},i}} P_k^{\mathrm{net}} - \sum_{k\in N_{\mathrm{d},n(i)}} P_{\mathrm{loss},k} \tag{4}$$

$$B_i = \sum_{k\in N_{\mathrm{d},i}} Q_k^{\mathrm{net}} - \sum_{k\in N_{\mathrm{d},n(i)}} Q_{\mathrm{loss},k} \tag{5}$$

$$\begin{aligned} V_i^2 = \{&V_{p(i)}^2 + 2(A_iR_i+B_iX_i) \\ &+ [V_{p(i)}^4 + 4(A_iR_i+B_iX_i)V_{p(i)}^2 \\ &- 4(A_iX_i-B_iR_i)^2]^{1/2}\}/2 \quad \forall i\in N \end{aligned} \tag{6}$$

$$V_0 = \frac{V_{\mathrm{hv}}}{m(1+tap\frac{\delta}{100})} \tag{7}$$

$$V_{\min} \le V_i \le V_{\max} \quad \forall i\in N \tag{8}$$

$$I_i \le I_{\max,i} \quad \forall i\in N \tag{9}$$

$$Q_{\min,i} \le Q_i^{\mathrm{gen}} \le Q_{\max,i} \quad \forall i\in N_{\mathrm{dg}} \tag{10}$$

$$tap \in D \tag{11}$$

The minimization of network losses is expressed by the objective function of (1), in which N is the total set of branches or network nodes, omitting the slack bus (node 0). Eqs. (2) and (3) calculate the active ($P_{\mathrm{loss},i}$) and reactive power loss ($Q_{\mathrm{loss},i}$) of i-th branch with respect to the corresponding resistance (R_i) and reactance (X_i). V_i stands for the voltage magnitude of i-th node, whereas A_i and B_i denote the active and reactive power flowing through the i-th branch, respectively. Furthermore, $N_{\mathrm{d},i}$ is the set of branches or network nodes located downstream of the i-th node, while $p(i)$ and $n(i)$ are the previous and next adjacent nodes to the i-th node, respectively. P_k^{net} and Q_k^{net} are the net injected active and reactive power of the k-th node.

The transformer is modeled as an equivalent series impedance referred to the LV side, connecting the slack bus with the main busbar (node 1) of the network. The discrete operation of the tap changer is applied on the slack bus (V_0), which is referred to the LV side and formulated in (7). V_{hv} denotes the voltage at HV side of the transformer, m is the nominal transformation ratio, tap is the tap position of transformer, while δ is the percent change in the transformation ratio per tap change.

Furthermore, constraints concerning the network operation are incorporated into the optimization problem. More specifically, (8) is employed to determine the permissible limits of network voltages, while (9) takes into account the thermal limit of lines. Additionally, the reactive power capability of each DG unit is also considered using (10), where Q_i^{gen} is the produced reactive power of the DG unit located at i-th node and N_{dg} is the set of nodes with DG units. Finally, the available tap positions of the transformer are considered in (11), where D is the corresponding discrete set.

The Volt/Var optimization problem of (1)-(11) presents two main drawbacks, which are related with the limited capabilities of conventional transformer. The first one is the increased computational complexity caused by the discrete nature of tap changer, transforming the Volt/Var control from a nonlinear into a mixed-integer nonlinear optimization problem. The second drawback is the fact that the voltage at main busbar is controlled in discrete steps by the conventional transformer, and thus the operational range of network voltages, as defined in (8), cannot be effectively exploited, eventually resulting in increased network losses.

B. Proposed Modifications

The inherent ability of SST to control the voltage at main busbar in a continuous manner can overcome the above-mentioned issues. More specifically, the Volt/Var control is transformed into a nonlinear optimization problem with reduced computational complexity, whereas the voltage operational limits can be fully exploited in order to further minimize nework losses. This feature of SST is investigated for the first time in the literature, since the majority of works focus on the participation of SST in the Volt/Var control as controllable reactive power source [11]–[15].

The voltage between slack bus and main busbar is decoupled due to the SST. Therefore, the Volt/Var optimization problem is now modified and formulated as expressed in (1)-(10), by omitting slack bus and replacing (7) and (11) with the following expressions:

$$V_1 = \frac{V_{\text{hv}}}{t} \tag{12}$$

$$t_{min} \le t \le t_{max} \tag{13}$$

where V_1 is the voltage magnitude of main busbar and t is the transformation ratio of SST, which is treated as a continuous variable, varying between minimum (t_{min}) and maximum (t_{max}) permissible limit, respectively.

IV. Simulation Results

In the following subsections, the improved performance of SST against conventional transformer is evaluated by conducting time-series deterministic and probabilistic simulations on an extended radial MV network.

A. System Under Study

The examined MV network is presented in Fig. 3, consisting of 10 DG units and 33 constant power loads. Furthermore, the network consists of 45 nodes, while the length and the impedance of lines are shown in Tables I and II, respectively. For the sake of simplicity, only one type of DG is considered, i.e., PV units, which are denoted with red color in Fig. 3, while black color corresponds to loads. PV units and loads are numbered according to their connection node and their rated values are presented in Table III, where the negative sign indicates power consumption. The power factor of loads is considered constant and equal to 0.95 lagging for the whole simulation period. Additionally, it is assumed that PV inverters can absorb reactive power with a minimum power factor of 0.85. A 150 kV/20 kV conventional transformer is considered with a rated power of 50 MVA, short-circuit voltage 12%, while the full load losses are 0.5%. The on-load tap changer range (D) is ± 8 with a voltage variation (δ) of 1.67% per tap change. Considering the SST, its transformation limits t_{min} and t_{max} coincide with those of the conventional transformer and are equal to 6.498 and 8.502, respectively.

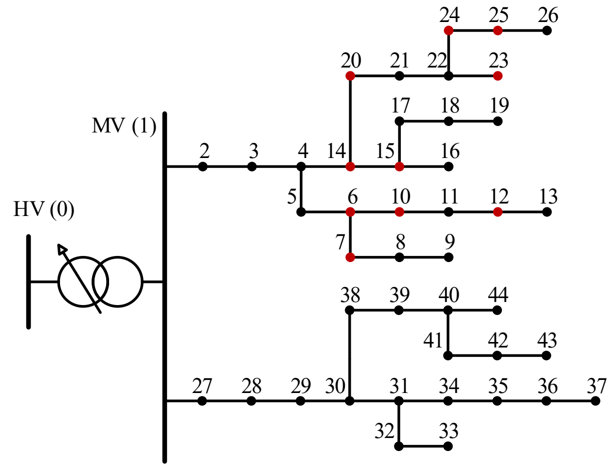

Fig. 3. Topology of the examined network.

TABLE I
NETWORK LINES LENGTH

Line Number	Length (km)
3,8,18,26,29,30,34,42,43	1
2,6,7,10,11,13,17,21,24,27,32,36,39,40	2
4,9,12,15,19,20,23,25,28,33,35,37,38,41,44	3
5,14,16,22,31	4

TABLE II
NETWORK LINES IMPEDANCE

Line Number	Impedance (Ω /km)
2,3,4,27,28,29,30	0.215+i0.334
5,6,10,11,12,13,14,15,16,20,21,22, 24,25,26,31,32,33,38,39,40,41,42,43	0.404+i0.386
7,8,9,17,18,19,23,34,35,36,37,44	0.576+i0.397

TABLE III
RATED ACTIVE POWER OF PV UNITS AND LOADS

Nodes	MW	Nodes	MW	Nodes	MW
7	0.60	6,14	2.00	10,20,25	1.00
12	0.70	8,37	-0.20	4,22,27,38,40	-0.60
13	-0.90	15,24	1.50	5,17,26,30,41	-0.30
23	0.50	29,35	-0.80	9,19,28,42,44	-0.40
31	-1.00	32,33	-0.70	2,11,21,34,36,43	-0.50
39	-1.20	3,16,18	-0.25		

The simulation period is 24 h with 1 min time interval for both deterministic and probabilistic simulations, while the control period of the Volt/Var control is considered equal to 1 min. In this paper, the Volt/Var optimization problem is solved at each time instant using GAMS [16]. More specifically, the mixed-integer nonlinear optimization problem of the conventional Volt/Var control is solved using the BONMIN solver, while the modified nonlinear optimization problem is solved employing the CONOPT solver.

B. Deterministic Simulations

In deterministic simulations, the Volt/Var optimization problem is solved assuming typical consumption and generation profiles. In this paper, normalized consumption and generation profiles, similar to those of Fig. 4, are arbitrary distributed to

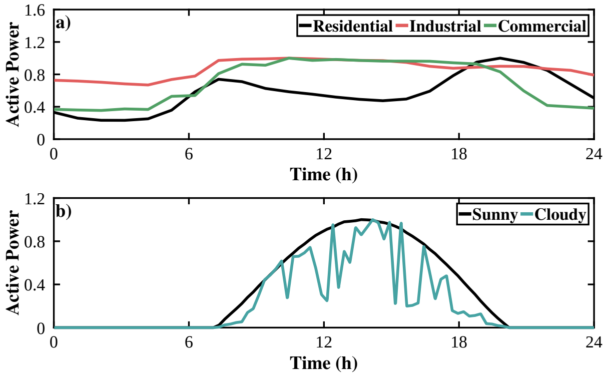

Fig. 4. Normalized profiles. (a) Consumption and (b) generation profiles.

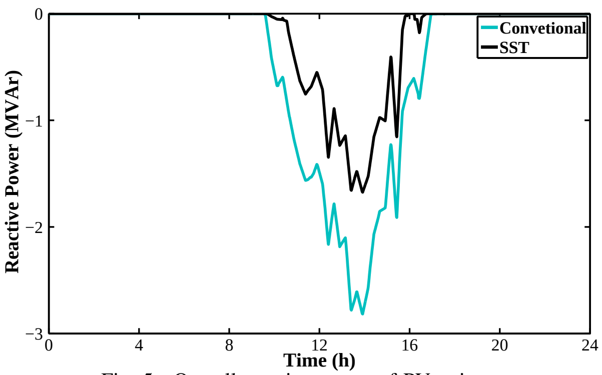

Fig. 5. Overall reactive power of PV units.

loads and PV units, respectively. The overall reactive power consumption of PV units is depicted in Fig. 5, while the voltages of two indicative network nodes are shown in Figs. 6 and 7, respectively. Furthermore, the transformation ratio and the equivalent tap position for both the conventional power transformer and SST are presented in Fig. 8.

Considering the SST, the overall reactive power consumption is reduced compared to the conventional transformer approach, as shown in Fig. 5. As a result, the daily energy losses of network are reduced by 2.8%, from 9.74 MWh to 9.47 MWh. Furthermore, network voltages remain within the permissible limits, which are defined at $\pm 5\%$ of nominal voltage [17]. This is also verified in Figs. 6 and 7, where the voltage profiles of the nodes presenting the maximum and minimum values are depicted.

Moreover, the conventional transformer uses discrete steps to regulate network voltages with a voltage variation of 1.67% per tap change. Therefore, during high generation periods, the voltage at node 43 remains well above the lower permissible limit, since a further tap change would reduce voltage below this limit. This inability to further reduce network voltages results in increased reactive power consumption from PV units, and thus increased energy losses. On the other hand, the SST can exploit the whole operational range of voltages, resulting in less reactive power consumption and energy losses, as shown in Fig. 5. This can be also verified in Fig. 8, where the conventional transformer keeps a constant trasformation ratio for the whole simulation period, whereas the SST continuously

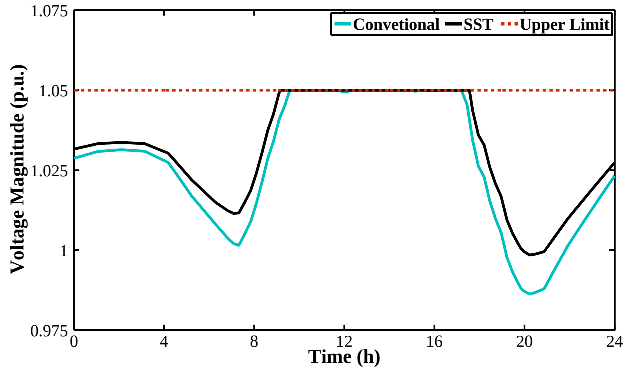

Fig. 6. Voltage profile of node 25.

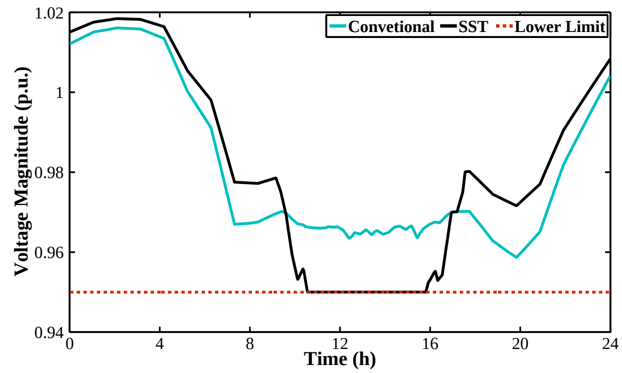

Fig. 7. Voltage profile of node 43.

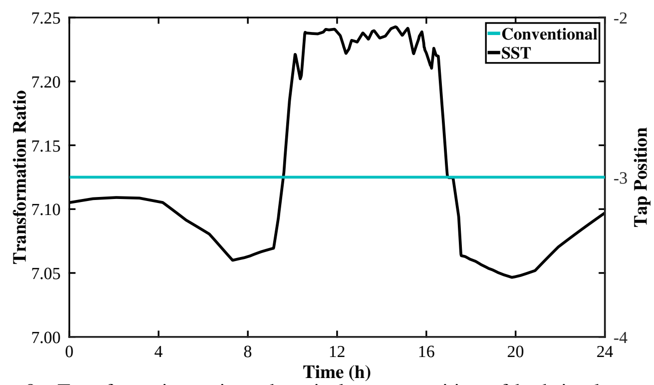

Fig. 8. Transformation ratio and equivalent tap position of both implementations.

varies its ratio based on the loading conditions. In this way, energy losses are minimized.

The total execution time of the conventional Volt/Var control strategy for one day simulation is equal to 4242.17 s, which is approximately equal to 1 h and 10 min. Thus, the conventional Volt/Var control may result in prohibitive execution times, especially in cases of extended distribution networks. On the other hand, the total execution time of the modified Volt/Var control is equal to 893.46 s, i.e., 15 min, which corresponds to a 78.93% reduction of the execution time. Therefore, the computational burden is reduced, allowing the real-time implementation of the modified Volt/Var control.

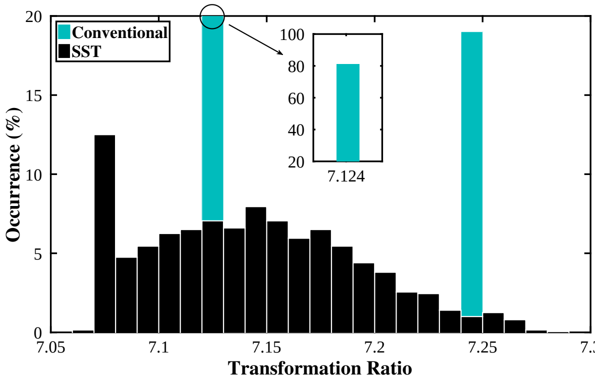

Fig. 9. Transformation ratio occurrence at 14:00.

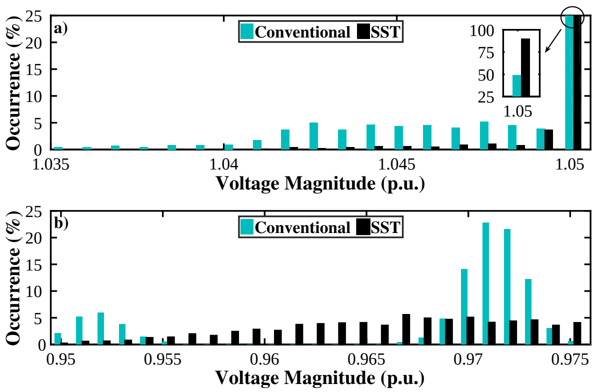

Fig. 10. Voltage occurrence at 14:00. a) node 25 and b) node 43.

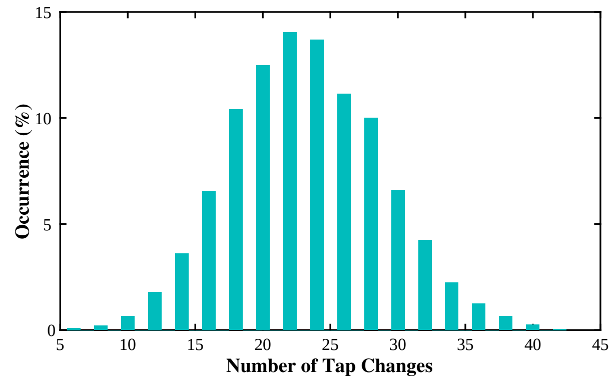

Fig. 11. Occurrence of the daily number of tap changes of the conventional transformer.

TABLE IV
DAILY ENERGY LOSSES (KWH)

	Min	Max	Mean	Std
Conventional	8140.24	8194.20	8170.28	7.79
SST	8005.06	8062.10	8037.06	7.88
Difference (%)	-1.66	-1.61	-1.63	1.15

TABLE V
EXECUTION TIME (S)

	Min	Max	Mean	Std
Conventional	3291.91	8517.73	4864.01	802.19
SST	717.83	893.89	850.38	15.15
Difference (%)	-78.19	-89.51	-82.25	-98.11

C. Probabilistic Simulations

The probabilistic performance evaluation of the SST is implemented by performing Monte Carlo (MC) simulations. Therefore, a 2000 sample of random consumption and generation values are generated for each time instant and the corresponding Volt/Var optimization problem is solved. As a result, the overall number of MC simulations is 5760000. It is assumed that loads uncertainty follows a normal distribution with mean values equal to the corresponding deterministic values of Section IV-B, whereas the standard deviation (std) equals to 5% of the mean values [18]. Additionally, the arbitrary generated values of PV units follow a beta distribution, where coefficients α and β are equal to 2.06 and 2.50, respectively, and are obtained using original historical data [19].

Indicative results of the MC simulations are presented in Figs. 9-11 and Tables IV, V. More specifically, assuming a specific time instant, the percentage occurrence of the transformation ratio for both the conventional transformer and SST is depicted in Fig. 9. Moreover, the corresponding percentage occurrence of the voltage magnitude for two indicative network nodes is presented in Fig. 10, while Fig. 11 shows the percentage occurrence of daily number of tap changes of the conventional transformer. Finally, the minimum, maximum, average, and standard deviation of the daily energy losses and of the corresponding execution time are presented in Tables IV and V, respectively.

According to the results obtained from MC simulations, similar conclusions can be drawn regarding the improved performance of SST against conventional transformer. In particular, SST adds an additional flexibility to network operation by varying its transformation ratio in a continuous manner compared to the discrete operation of on-load tap changer of the conventional operation. This is also validated in Fig. 9, where the conventional transformer operates in two discrete states against the continuous operation of SST. This has an effect on network voltages as shown in Fig. 10, where it can be observed that, contrary to the conventional transformer, SST can exploit to a greater extent the operation range of voltages. Therefore, this results in reduced network losses, as verified in Table IV.

By introducing consumption and generation uncertainty in the conventional Volt/Var control, a large number of tap changes is needed to minimize network losses as shown in Fig. 11, resulting in a reduced lifetime of the on-load tap changer. Therefore, in practice, a new constraint is introduced to the optimization problem to reduce the number of tap changes, which, however, increases the network losses. On the other hand, SST has no operational limits regarding the frequency of changing the transformation ratio, without affecting the minimization of network losses.

Finally, considering the computational burden, the total execution time when the SST participates in the Volt/Var control is reduced compared to the conventional transformer. Furthermore, it presents a significantly reduced standard deviation, validating the improved performance of the SST against the conventional transformer.

V. Conclusions

In this paper, the performance of SST on voltage regulation of active distribution networks is investigated. The conventional Volt/Var optimization problem is properly modified to incorporate the new operation capabilities of SST. Time-series deterministic and probabilistic simulations are performed to thoroughly examine the performance of SST compared to conventional transformer equipped with on-load tap changer. Simulation results reveal that SST presents an improved performance against the conventional transformer in terms of voltage regulation, minimization of network losses, and computational burden.

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