Improving Loadability in Unbalanced Distribution Network using Flexible Step Voltage Regulator

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***Abstract*—Rapid load growth is increasing the strain on the distribution network, resulting in unacceptable voltage drops. The loadability limits on the distribution network can be enhanced by using voltage control devices. This paper examines the impact of the Flexible Step Voltage Regulator (FSVR) on the loadability of unbalanced distribution networks. FSVR can independently control the magnitude and angle of voltage in each phase, resulting in superior voltage regulation than traditional Step Voltage Regulators (SVR). To demonstrate the effect of FSVR on enhancing loadability, simulation tests are done on an IEEE 13 bus unbalanced distribution network.**

***Index Terms*—Flexible Step Voltage Regulator, voltage control, load multiplier, loadability, unbalanced distribution network**

I. Introduction

With a rise in living standards, the rate of electricity consumption growth is accelerating. The incorporation of variable renewable generation and electric vehicle loads complicates grid operation. In this situation, the grid operator must optimize network utilization. A variety of control mechanisms can be utilized by the grid operator to increase the distribution network's loading capacity [1], [2].

Controls may originate from either the consumer end or the network operator end. Demand response, load shifting, and control of distributed generator inverters are all examples of consumer-side controls. Authors in [3]–[5] have used demand response schemes to improve voltage stability in the distribution network. Distribution networks are typically unbalanced, so conventional strategies for balanced transmission networks may not be effective. The network must be modeled in three-phase detail, and the load for each phase can vary. Load shifting between phases is used to improve the overall loading capability is used in [6], [7]. Inverter control strategies were used for improving the voltage profile, thereby improving the overall loadability in [8]–[10]. All these methods require cooperation and coordination with the consumers.

The alternate approach is using controls available with network operators. These are typically in the form of network reconfiguration, capacitor bank, tap-changing transformer and Step Voltage Regulator (SVR). Network reconfiguration was used to improve the loadability in [11], [12]. However, it is impractical to frequently reconfigure a network on a daily basis due to the fluctuating nature of demand. While [13], [14] have used capacitor banks to improve voltage, [15], [16] have used tap-changing transformers. SVR is a non-isolated version of tap-changing transformer, working similarly to an autotransformer. SVR is more cost-effective than tap-changing transformers since it requires less copper for equivalent ratings. Therefore, SVR is the better solution for distribution networks. SVR is used to improve the voltage quality in [17], [18]. An advanced version of SVR with power electronics assisted tap-changing is proposed in [19].

In a recent paper, Flexible Step Voltage Regulator (FSVR), an advanced version of SVR, was proposed [20]. It can independently control the magnitude and angle of the voltage, whereas SVR can only control the magnitude. Consequently, FSVR can control voltage more effectively, especially when the network is unbalanced. Therefore, this work uses FSVR for voltage control in an unbalanced distribution network to improve its loadability.

The main contributions of the paper are

1) The optimal values of FSVR and SVR parameters are found using Grey Wolf Optimization (GWO) algorithm.
2) An algorithm to find the maximum loadability in the distribution network with optimal tap settings of FSVR and SVR is presented.
3) Simulation studies on IEEE 13 bus unbalanced distribution network is presented to compare the voltage regulation capability of FSVR and SVR to improve loadability.

II. Background

A. Mathematical model of FSVR

FSVR is constructed based on Multi Winding Transformer (MWT) architecture. It can be used in combination with the traditional distribution transformer in unbalanced distribution networks.

The basic structure of FSVR is given in figure 1 and the voltage equation is given by [21]

$$\begin{bmatrix} V_{oa} \\ V_{ob} \\ V_{oc} \end{bmatrix} = \begin{bmatrix} 1+\alpha_{a1} & \alpha_{a2} & \alpha_{a3} \\ \alpha_{b3} & 1+\alpha_{b1} & \alpha_{b2} \\ \alpha_{c2} & \alpha_{c3} & 1+\alpha_{c1} \end{bmatrix} \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} \quad (1)$$

where,
V_{oa}, V_{ob}, V_{oc}= Phase voltages at the output side of FSVR

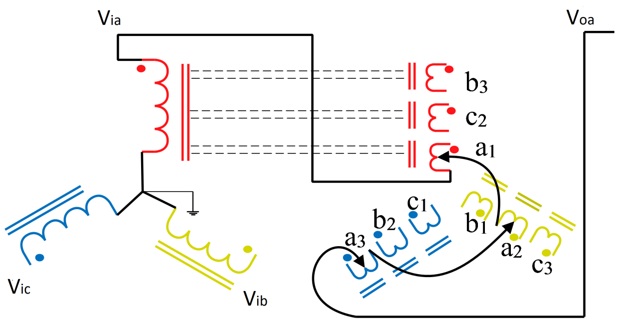

Fig. 1. MWT based FSVR circuit configuration

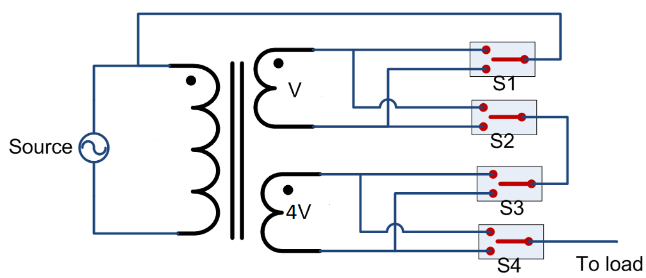

Fig. 2. Circuit for one winding of FSVR

α_{a1}, α_{a2}, α_{a3}, α_{b1}, α_{b2}, α_{b3}, α_{c1}, α_{c2}, α_{c3} = Equivalent tap-setting for each of the nine FSVR windings.
V_{ia}, V_{ib}, V_{ic}= Phase voltages on the FSVR input side.

The equivalent 2-port model of FSVR is used for backward-forward sweep-based power flow analysis:

$$\begin{aligned} A &= \begin{bmatrix} 1+\alpha_{a1} & \alpha_{a2} & \alpha_{a3} \\ \alpha_{b3} & 1+\alpha_{b1} & \alpha_{b2} \\ \alpha_{c2} & \alpha_{c3} & 1+\alpha_{c1} \end{bmatrix}^{-1} \\ B &= 0 \\ C &= 0 \\ D &= \begin{bmatrix} 1+\alpha_{a1} & \alpha_{a2} & \alpha_{a3} \\ \alpha_{b3} & 1+\alpha_{b1} & \alpha_{b2} \\ \alpha_{c2} & \alpha_{c3} & 1+\alpha_{c1} \end{bmatrix} \end{aligned} \tag{2}$$

FSVR has three secondary windings for each phase, totaling nine windings for a three-phase system. Each winding is further subdivided into two sub-windings that are linked to each other through single pole double throw (SPDT) switches. The circuit diagram for one winding of FSVR is shown in Figure 2. The sub-windings are set up using these switches in one of the three working modes aiding mode, opposing mode, or bypass mode. Therefore, controlling the switches emulates changing of tap settings of FSVR. If the voltage ratings of the two sub-windings are 'V' and '4V', 9 different values of effective voltages (V_{eff}) can be obtained by various switching combinations. The various switching combinations and their effective voltages are shown in Table I. Since each winding can have 9 values, a total of 729 (9^3) switching combinations are possible with all 3 phases.

TABLE I
EFFECTIVE VOLTAGE WITH VARIOUS SWITCH COMBINATIONS

S1	S2	S3	S4	V_{eff}
1	0	1	0	-5V
0	0	1	0	-4V
0	1	1	0	-3V
1	0	0	0	-V
0	0	0	0	0
0	1	0	0	+V
1	0	0	1	+3V
0	0	0	1	+4V
0	1	0	1	+5V

In percentage terms, each phase is capable of $\pm 5\%$ voltage regulation. The 3 phases combined can result in maximum voltage regulation of $\pm 10\%$.

B. Mathematical model of SVR

The traditional SVR is comparable to a three-phase autotransformer with tap switching. The SVR output voltage can be varied by changing its tap settings. SVR can modify only voltage magnitude, and not the phase angle. The voltage equation of SVR for each phase is given by

$$V_{op} = (1+\alpha_p)V_{ip} \tag{3}$$

where,
V_{op} = Output voltage of SVR for phase 'p'
α_p = Tap setting of SVR for phase 'p'
V_{ip} = Input voltage of SVR for phase 'p'
p= a,b,c

The equivalent 2-port SVR model parameters for power flow analysis are given by [22]

$$\begin{aligned} A &= \begin{bmatrix} 1+\alpha_a & 0 & 0 \\ 0 & 1+\alpha_b & 0 \\ 0 & 0 & 1+\alpha_c \end{bmatrix}^{-1} \\ B &= 0 \\ C &= 0 \\ D &= \begin{bmatrix} 1+\alpha_a & 0 & 0 \\ 0 & 1+\alpha_b & 0 \\ 0 & 0 & 1+\alpha_c \end{bmatrix} \end{aligned} \tag{4}$$

To enable fair comparison with FSVR, the SVR considered in this work also has a maximum voltage regulation of $\pm 10\%$. There are 21 positions on the SVR: 10 for increasing voltage, 10 for decreasing voltage, and 1 for neutral position. Each step change corresponds to 1% voltage variation.

III. METHODOLOGY

A. Optimization problem

The objective of the optimization problem is to find the values of FSVR or SVR parameters, which lead to the least deviation of voltage from its nominal value. The objective function is defined by Equation

$$\text{Min. } V_{\text{dev,max}} \tag{5}$$

$V_{\text{dev,max}}$ is defined as follows

$$V_{\text{dev,max}} = \max_{i=1..n}\left(\max_{p=a,b,c}|V_{ip} - V_{\text{nom}}|\right) * 100 \quad (6)$$

where,
V_{ip} = Voltage magnitude in phase p at bus i (in p.u.)
n = number of buses.
V_{nom}= Nominal voltage (usually taken as 1 p.u.)

The constrains for the optimization problem are given in equations 7 to 11.

$$\begin{bmatrix} J_{ia} \\ J_{ib} \\ J_{ic} \end{bmatrix} = \begin{bmatrix} \left(S_{ia}/V_{ia}\right)^* \\ \left(S_{ib}/V_{ib}\right)^* \\ \left(S_{ic}/V_{ic}\right)^* \end{bmatrix} \quad (7)$$

where,
J_{ia}, J_{ib}, J_{ic}= current injections at node i
S_{ia}, S_{ib}, S_{ic}= scheduled (known) power injections at node i
V_{ia}, V_{ib}, V_{ic}= voltages at node i

$$\begin{bmatrix} I_{ia} \\ I_{ib} \\ I_{ic} \end{bmatrix} = C \begin{bmatrix} V_{ja} \\ V_{jb} \\ V_{jc} \end{bmatrix} + D \left[- \begin{bmatrix} J_{ja} \\ J_{jb} \\ J_{jc} \end{bmatrix} + \sum_{m \in M} \begin{bmatrix} I_{ma} \\ I_{mb} \\ I_{mc} \end{bmatrix} \right] \quad (8)$$

where,
I_{ia}, I_{ib}, I_{ic}= line currents at node i
M = set of line sections connected to node j

$$\begin{bmatrix} V_{ja} \\ V_{jb} \\ V_{jc} \end{bmatrix} = A^{-1} \begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} - A^{-1}B \begin{bmatrix} I_{ja} \\ I_{jb} \\ I_{jc} \end{bmatrix} \quad (9)$$

where,
A, B, C, D= Two port parameters in the form of 3*3 matrices

$$P_{ij} < P_{ij\_\text{max}} \quad (10)$$

where,
P_{ij}= Power flow in the line connecting bus i to bus j

$$(VUF)_i = \left|\frac{V_i^-}{V_i^+}\right| * 100 \le (VUF)_{\text{max}} \quad (11)$$

where,
$(VUF)_i$= Voltage unbalance index (VUF) at bus i
V_i^- = Negative sequence component of voltage at bus i
V_i^+ = Positive sequence component of voltage at bus i
$(VUF)_{\text{max}}$= Maximum limit of voltage unbalance factor

The equations 7 to 9 correspond to backward-forward sweep power flow algorithm [22]. Equation 10 ensures power flow in the distribution lines are within its maximum limits. Equation 11 defines VUF to be within its maximum limit.

The FSVR and SVR parameters are the optimization's control variables. The FSVR parameters are the tap settings for its nine windings. There are nine possible values for each winding: -0.05, -0.04, -0.03, -0.01, 0, 0.01, 0.03, 0.04, and 0.05. The parameters for SVR are the tap specifications for its three windings. Each winding has 21 discrete values ranging from -0.10 to 0.10 in 0.01-step increments.

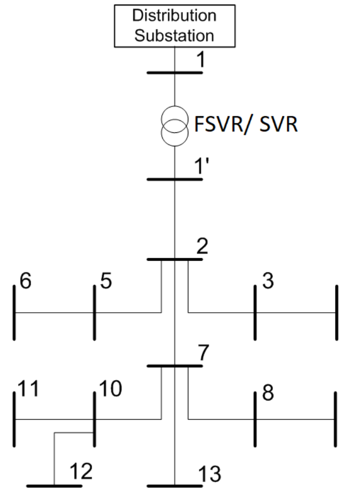

Fig. 3. Single line diagram of IEEE 13 bus unbalanced distribution network

Equations 5 to 11 are solved with the GWO algorithm. The GWO method is based on the social hierarchy and hunting behavior of grey wolves, who endeavor to encircle their prey prior to capturing it [23]. The method is based on swarm intelligence and can converge to optimal solutions for mixed-integer and nonlinear problems, such as this work.

B. Algorithm to find maximum loadability

Loadability analysis is conducted by using a load multiplier factor (λ). The aim of algorithm is to find the critical load multiplier factor (λ_c) which is the maximum value without violating voltage limits, $V_{dev,\text{limit}}$. The loads in the network are modified by Equation 12.

$$\begin{aligned} P_{L\_ip} &= P_{L0\_ip}(1+\lambda) \\ Q_{L\_ip} &= Q_{L0\_ip}(1+\lambda) \end{aligned} \quad (12)$$

where,
P_{L_ip}, Q_{L_ip} = Real power and reactive power consumption by loads in phase p at bus i.

The algorithm to find λ_c is given below.

Algorithm 1: To find critical loading factor

1 Initialize $\lambda = 0$
2 Solve equations 5 to 11 to find optimal parameters of FSVR (or SVR)
3 Calculate $V_{\text{dev,max}}$ corresponding to the optimal parameters
4 If $V_{dev,max} \le V_{dev,limit}$, continue
Else, goto step 6
5 $\lambda = \lambda + 0.05$, goto step 2.
6 $\lambda_c = \lambda - 0.05$, STOP

IV. RESULTS

Loadability analysis is conducted on IEEE 13 bus unbalanced distribution network shown in Figure 3 [24]. The

TABLE II
RESULTS OF OPTIMIZATION ON IEEE 13 BUS NETWORK

Loading factor (λ)	Optimal value of tap settings with FSVR										Optimal SVR tap settings			
	α_{a1}	α_{a2}	α_{a2}	α_{b1}	α_{b2}	α_{b3}	α_{c1}	α_{c2}	α_{c3}	$V_{\text{dev,max}}$	α_a	α_b	α_c	$V_{\text{dev,max}}$
0	0.03	-0.01	-0.03	-0.01	0	-0.01	0.03	-0.04	-0.03	2.33	0.06	0.01	0.07	2.51
0.05	0.01	-0.04	-0.05	-0.01	-0.04	0.01	0.03	-0.04	-0.04	2.33	0.06	0	0.07	2.41
0.1	0.05	-0.01	-0.01	0	0	-0.01	0.05	-0.01	-0.04	2.52	0.06	-0.01	0.07	2.88
0.15	0.04	0.01	-0.05	0.04	0.05	0.01	0.03	-0.05	-0.04	2.49	0.07	0.01	0.08	2.84
0.2	0.05	-0.01	-0.03	0	0	-0.01	0.03	-0.05	-0.05	2.66	0.07	-0.01	0.08	2.73
0.25	0.04	-0.01	-0.05	0	0	0.01	0.05	-0.05	-0.01	2.70	0.07	-0.01	0.08	3.23
0.3	0.05	0	-0.04	0	-0.01	0	0.04	-0.05	-0.04	2.85	0.08	0.01	0.09	3.17
0.35	0.03	-0.04	-0.05	-0.01	-0.01	0	0.04	-0.05	-0.05	3.00	0.08	0	0.09	3.10
0.4	0.04	-0.04	-0.03	-0.03	-0.01	-0.04	0.05	-0.04	-0.05	3.16	0.07	-0.01	0.09	3.56
0.45	0.05	-0.01	-0.05	0.01	0	0.01	0.05	-0.05	-0.04	3.18	0.08	0.01	0.1	3.51
0.5	0.05	-0.03	-0.05	0	-0.01	-0.01	0.05	-0.05	-0.05	3.33	0.08	-0.01	0.1	3.39
0.55	0.05	-0.01	-0.05	0.01	0	0	0.05	-0.05	-0.05	3.72	0.08	-0.01	0.1	3.91
0.6	0.05	-0.01	-0.05	0	0.01	-0.01	0.05	-0.05	-0.05	4.15	0.08	-0.02	0.1	4.38
0.65	0.05	-0.01	-0.05	-0.01	0	-0.01	0.05	-0.05	-0.05	4.62	0.08	-0.02	0.1	4.90
0.7	0.05	-0.03	-0.05	-0.01	-0.03	0.05	0.05	-0.05	-0.05	5.15	0.08	-0.02	0.1	5.43
0.75	0.05	-0.03	-0.05	-0.05	-0.05	0.01	0.05	-0.05	-0.05	5.66	0.08	-0.03	0.1	5.92
0.8	0.05	-0.01	-0.05	-0.03	0.01	-0.01	0.05	-0.05	-0.05	6.09	0.08	-0.03	0.1	6.46
0.85	0.05	-0.01	-0.05	0	0.01	0.01	0.05	-0.05	-0.05	6.67	0.08	-0.04	0.1	6.96
0.9	0.05	-0.01	-0.05	-0.03	0	0	0.05	-0.05	-0.05	7.13	0.08	-0.04	0.1	7.51
0.95	0.05	-0.01	-0.05	-0.05	0	-0.01	0.05	-0.05	-0.05	7.63	0.08	-0.05	0.1	8.04
1	0.05	-0.01	-0.05	0	0.05	0.04	0.05	-0.05	-0.05	8.14	0.08	-0.05	0.1	8.57
1.05	0.05	-0.01	-0.05	0	0.05	0.04	0.05	-0.05	-0.05	8.70	0.08	-0.05	0.1	9.14
1.1	0.05	-0.01	-0.05	-0.01	0.05	0.04	0.05	-0.05	-0.05	9.21	0.08	-0.06	0.1	9.66
1.15	0.05	-0.01	-0.05	-0.05	0.01	0	0.05	-0.05	-0.05	9.76	0.08	-0.06	0.1	10.24
1.2	0.05	-0.01	-0.05	-0.04	0.03	0.01	0.05	-0.05	-0.05	10.34				

network has 8 loads with total of 899.41 kW, 530.57 kVar in Phase a; 596.11 kW, 294.6 kVar in Phase b; and 870.48 kW, 560.82 kVar in Phase c. All loads are assumed to be star connected and modeled as constant power loads. The bus 1 substation serves the entire capacity, so it is taken as the slack bus. The SVR or FSVR is installed on bus 1, creating a new virtual bus, 1'. The distribution lines are modeled with three-phase detail. Other reactive power compensation devices in the network are neglected. The maximum voltage deviation without any compensating devices is 9.84 %. It is assumed maximum voltage deviation allowed is $\pm 10\%$, hence the load is already near its maximum limit.

The optimization algorithm using the GWO method is run by adding FSVR (or SVR) near the substation bus in the network. The line power flow limit, P_{ij_max} is taken as 1500 kW and the $(VUF)_{\text{max}}$ is 5 %. The optimal values of FSVR and SVR parameters for various loading factors are given in Table II. The critical value of load multiplying factor, λ_c should have voltages within the maximum voltage deviation of $\pm 10\%$. From the Table II, λ_c with FSVR compensation is 1.15. When λ is increased beyond this value, voltage deviation exceed 10 %. For the SVR compensation case, λ_c is only 1.10 as evident from Table II. Therefore, it can be concluded that FSVR performs better than traditional SVR in improving loadability.

V. CONCLUSION

This research illustrates that FSVR is effective in increasing the loadability of distribution networks and provides supporting evidence. The results of a simulation analysis carried out on the IEEE 13 bus network shown that FSVR is superior than classic SVR in terms of its capacity to increase loadability. This is possible due to the fact that FSVR has the ability to regulate both the magnitude and the angle of the voltage. Future research incorporating uncertainties in load and generation can provide a more accurate picture of loadability with FSVR.

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REFERENCES

[1] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, "Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2999–3008, 2017.

[2] P. Aristidou, G. Valverde, and T. Van Cutsem, "Contribution of distribution network control to voltage stability: A case study," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 106–116, 2017.

[3] R. Kang, Y. Xu, Z. Y. Dong, and D. J. Hill, "Demand response-based preventive-corrective control against short-term voltage instability in power systems," in *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, 2017, pp. 1–5.

[4] Y. Dong, X. Xie, W. Shi, B. Zhou, and Q. Jiang, "Demand-response-based distributed preventive control to improve short-term voltage stability," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4785–4795, 2018.

[5] M. Yao, D. K. Molzahn, and J. L. Mathieu, "An optimal power-flow approach to improve power system voltage stability using demand response," *IEEE Transactions on Control of Network Systems*, vol. 6, no. 3, pp. 1015–1025, 2019.

[6] S. Sun, B. Liang, M. Dong, and J. A. Taylor, "Phase balancing using energy storage in power grids under uncertainty," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 3891–3903, 2016.

[7] F. Shahnia, P. J. Wolfs, and A. Ghosh, "Voltage unbalance reduction in low voltage feeders by dynamic switching of residential customers among three phases," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1318–1327, 2014.

[8] Y. Z. Gerdroodbari, R. Razzaghi, and F. Shahnia, "Improving voltage regulation and unbalance in distribution networks using peer-to-peer data sharing between single-phase pv inverters," *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2629–2639, 2022.

[9] A. Tyagi, M. Nazir, K. Kumar, V. V. Tyagi, and B. Kumar, "Optimal utilization of reactive power capabilities of distributed solar pv inverter," in *2022 22nd National Power Systems Conference (NPSC)*, 2022, pp. 30–34.

[10] T. Hathiyaldeniye, U. D. Annakkage, N. Pahalawaththa, and C. Karawita, "A comparison of inverter control modes for maintaining voltage stability during system contingencies," *IEEE Open Access Journal of Power and Energy*, vol. 9, pp. 55–65, 2022.

[11] M. Aman, G. Jasmon, A. Bakar, and H. Mokhlis, "Optimum network reconfiguration based on maximization of system loadability using continuation power flow theorem," *International Journal of Electrical Power & Energy Systems*, vol. 54, pp. 123–133, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S014206151300286X

[12] A. Tyagi, A. Verma, and P. Bijwe, "Reconfiguration for loadability limit enhancement of distribution systems," *IET Generation, Transmission & Distribution*, vol. 12, no. 1, pp. 88–93, 2018.

[13] R. Delfianti, O. Penangsang, A. Soeprijanto, N. H. Rohiem, N. P. U. Putra, and T. Suheta, "Application of particle swarm optimization algorithm for scheduling of capacitor bank switching to improve voltage," in *2021 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT)*, 2021, pp. 245–249.

[14] A. Hasibuan, M. Isa, I. M. A. Nrartha, and S. Hardi, "Improving voltage profile of 150 kv transmission line in aceh subsystem with capacitor bank installation," in *2019 3rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, 2019, pp. 140–144.

[15] K. M. Muttaqi, A. D. T. Le, M. Negnevitsky, and G. Ledwich, "A coordinated voltage control approach for coordination of oltc, voltage regulator, and dg to regulate voltage in a distribution feeder," *IEEE Transactions on Industry Applications*, vol. 51, no. 2, pp. 1239–1248, 2015.

[16] C. Li, V. R. Disfani, H. V. Haghi, and J. Kleissl, "Coordination of oltc and smart inverters for optimal voltage regulation of unbalanced distribution networks," *Electric Power Systems Research*, vol. 187, p. 106498, 2020.

[17] C. Toh, C. Lock, S. Chen, and S. Choi, "A voltage quality improvement solution using step dynamic voltage regulator," in *PowerCon 2000. 2000 International Conference on Power System Technology. Proceedings (Cat. No.00EX409)*, vol. 2, 2000, pp. 983–988 vol.2.

[18] B. Kim, K.-S. Ryu, D.-J. Kim, Y.-H. Nam, H. Ko, and H.-C. Kim, "A study on the voltage control method of primary feeder by the energy storage system and step voltage regulator," *IFAC-PapersOnLine*, vol. 52, no. 4, pp. 431–436, 2019, iFAC Workshop on Control of Smart Grid and Renewable Energy Systems CSGRES 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405896319305853

[19] K. DSouza, Y. Wang, G. Cakir, M. Baran, and T. Zhao, "Power electronics assisted voltage regulator: An effective solution for mitigating voltage variations caused by high penetration pv on a distribution system," in *2021 IEEE 12th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2021, pp. 1–5.

[20] B. K C, A. Verma, and S. K. Chattopadhyay, "Flexible step-voltage regulator for unbalanced distribution networks," *IEEE Transactions on Industry Applications*, vol. 58, no. 6, pp. 7002–7012, 2022.

[21] K. C. Bevin, A. Verma, and S. K. Chattopadhyay, "Alternate power flow controller for voltage control in an unbalanced distribution network," in *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2020, pp. 1–4.

[22] W. H. Kersting, *Distribution System Modeling and Analysis*. CRC Press, 2012.

[23] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey wolf optimizer," *Advances in Engineering Software*, vol. 69, pp. 46 – 61, 2014.

[24] IEEE PES AMPS DSAS Test Feeder Working Group. 1992 test feeder cases. [Online]. Available: https://site.ieee.org/pes-testfeeders/resources/