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Assessing STATCOM-Enabled Reactive Power Control in Fragile Power Transmission Systems: A Case Study Perspective

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ABSTRACT

The burgeoning energy demands induced by modern civilization necessitate the procurement of additional electrical energy reserves to effectively address this escalating challenge. However, the installation of new power generation units necessitates building/upgrade of accompanying transmission infrastructure, a task fraught with complexities. To augment the loading capacity of existing transmission lines, power engineers have devised efficient solutions, one of which involves the integration of novel devices. This paper delves into the management of reactive power within vulnerable transmission networks, focusing particularly on the pivotal role of Flexible AC Transmission System (FACTS) devices. Among the diverse array of FACTS technologies engineered to fortify grid resilience, the Static Synchronous Compensator (STATCOM) which emerges as a transformative asset. The paper explores the integration of STATCOM within the 132 kV transmission network of the Diyala city ring power system to enhance its stability and operational efficiency. Simulations of the Diyala power network and load flow analysis were conducted using MATLAB/Simulink environment. The results unveiled a notable enhancement in power quality upon the integration of STATCOM, as compared to the base scenario devoid of such augmentation. These findings bear significant implications, offering valuable insights for the Iraqi grid operator and other nations grappling with analogous challenges pertaining to frail power networks. Incorporating such advanced devices into national electrical systems could potentially mitigate operational inefficiencies, defer infrastructure investment and bolster overall grid resilience.

1. INTRODUCTION

Electricity plays a pivotal role in the operation of contemporary societies and economies, with its significance continually amplifying as electricity-dependent technologies [1]. Recently, power generation stands as the primary contributor to global carbon dioxide (CO_2) emissions [2]. However, it also stands at the forefront of the transition towards achieving net zero emissions, primarily facilitated by the swift proliferation of renewable energy sources such as solar and wind power [3]. Balancing the imperative of ensuring consumers' access to secure a cost-effective electricity alongside the imperative of mitigating global CO_2 emissions represent a fundamental challenge within the energy transition paradigm [4].

In 2023, global electricity demand experienced a comparatively moderate increase of 2.2%, marking a decline from the 2.4% growth observed in 2022. Nevertheless, a trajectory toward heightened growth is anticipated during the forecast period spanning 2024 to 2026, with a projected growth rate of 3.4% [5]. Emerging markets are anticipated to sustain their prominent role in propelling electricity demand, akin to their pivotal contribution observed in 2023. The enduring ramifications of the energy crisis reverberated throughout 2023, manifesting in elevated levels of inflation, heightened interest rates, and substantial debt burdens, collectively exerting downward pressure on economies worldwide.

However, power system stability encompasses the capability of a power system to maintain a consistent operational state under normal conditions and to restore equilibrium satisfactorily subsequent to any disturbances [6]. Voltage stability within the power system signifies the ability of voltage to return to its nominal operating level following a disturbance. Diverse factors, including constraints on generator reactive power, transmission line capacity, and load characteristics, exert an influence on power system voltage stability [7]. Consequently, the regulation of reactive power is imperative to ensure that bus voltages across the entirety of the system remain within acceptable parameters for optimal power system functionality [8-10]. However, owing to the inherent limitation of transferring reactive power over extensive distances due to increased losses, voltage regulation is achieved by implementing appropriate compensatory devices strategically positioned at specific locations.

In addressing power quality concerns, the deployment of Flexible Alternating Current Transmission System (FACTS) devices within power systems has garnered escalating attention in recent years, owing to their multifaceted advantages [11, 12]. These benefits encompass enhancements in voltage profile, mitigation of power losses, and augmentation of overall system reliability and safety. Nevertheless, the process of ascertaining the optimal category, placement, and magnitude of FACTS devices poses a formidable optimization challenge. This challenge stems from the intricate nature of the optimization task, characterized by mixed-integer, nonlinear, and nonconvex constraints [13-16]. Figure 1 exhibits the FACTS devices.

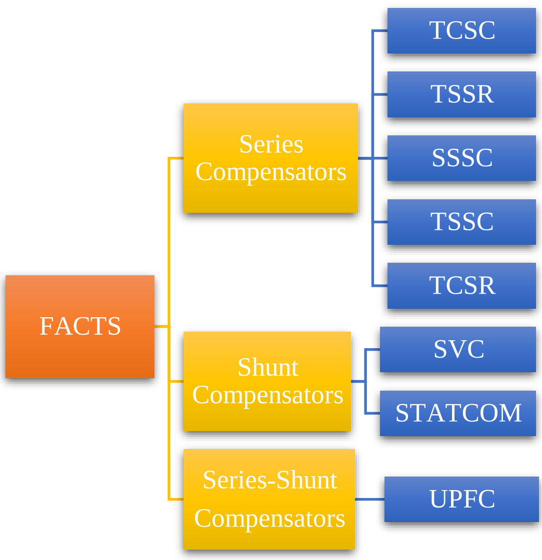

Figure 1. The FACTS devices

In this context, the static synchronous compensator (STATCOM), a power electronic shunt apparatus, is classified within the FACTS family. Its operational mechanism draws parallels with that of rotary synchronous compensators or generators, albeit with enhanced reliability attributed to its rapid response capabilities. This intrinsic association has bestowed upon the STATCOM its nomenclature. Distinguishing itself from static VAR compensators, with which it shares substantial functionalities, the STATCOM is characterized by its superior performance. It finds widespread application in the regulation of alternating current within power transmission networks [17, 18]. Figure 2 demonstrates the STATCOM device.

To clarify, utilizing power electronic voltage source converters, including Insulated Gate Bipolar Transistors (IGBTs), Gate Turn-Off Thyristors (GTOs), among others, STATCOMs emulate a source or sink for the AC reactive power within an electrical transmission network. This capability facilitates the regulation of reactive power flow throughout the transmission grid, thereby enhancing its transient stability. Furthermore, when interfaced with a power source, STATCOMs can effectively deliver active AC power [19-21]. Their utility extends beyond mere reactive power control; STATCOMs are particularly advantageous due to their capacity to mitigate voltage fluctuations, thereby contributing significantly to grid stability. Furthermore, a recent investigation into power quality (PQ) has determined that voltage sags, swells, harmonics, and related phenomena occurring within medium voltage power system are significantly prevalent PQ issues.

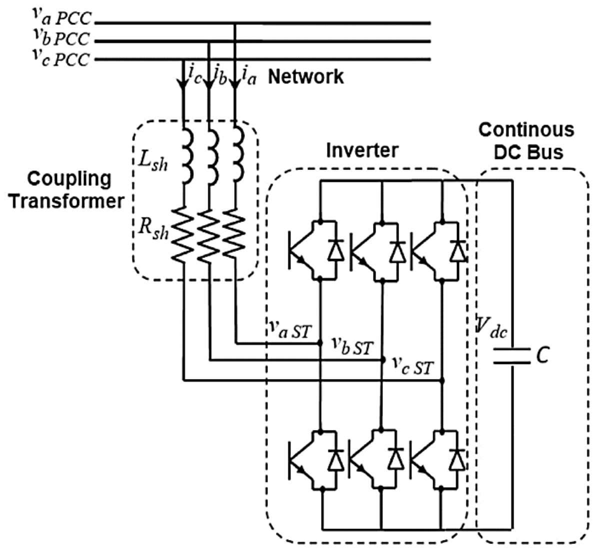

Figure 2. The STATCOM device

These manifestations are recognized as the foremost contributors to PQ concerns. Such PQ challenges pose substantial risks to sensitive loads, potentially resulting in significant financial ramifications amounting to millions of dollars in losses [22]. This assertion is substantiated by data from the Department of Energy (DOE), which suggests that the economic impact of electrical power outages for a brokerage enterprise can amount to approximately USD $6.50 million per hour. Additionally, in European nations, the influence of PQ issues on industry and commerce is estimated to be around $10.0 billion [23]. Therefore, further efforts are to be made such that economic and reliable operation of power system is attained, especially sensitive infrastructures that require major overhauls such as the case in Iraq. In this regard, this paper investigates the technical advantages of inserting FACTs devices into the Iraqi power system so as improving its current power quality status and defer massive cost incurred by major network upgrade.

2. RELEVANT STUDIES

Currently, STATCOM is a prominent subject of study and is increasingly being implemented and deployed in many countries. Numerous studies have been dedicated to investigate the efficacy of utilizing STATCOM devices for reactive power control in vulnerable power transmission systems. Tien et al. [24] compared the direct and indirect algorithms of the Newton-Raphson method for analyzing load flow in various power systems integrating STATCOM. The study revealed that the direct algorithm exhibited superior performance in terms of convergence time and accuracy compared to the indirect approach.

As stated by Bhukya and Mahajan [25], integrating STATCOM into the power system effectively eliminates voltage disturbances during fault occurrences. By implementing suitable control strategies for STATCOM operation, the overall stability of the power system is enhanced, as observed in improvements in rotor angle stability. In the reference [26], a comparative analysis of SVC and STATCOM is conducted, highlighting that optimal placement of SVC can boost line loading by up to approximately 14%. However, employing STATCOM yields superior results in terms of power system loadability and voltage profile enhancement. In another study [27], researchers deployed distributed STATCOM (D-STATCOM) in an 8-bus system to mitigate voltage sags caused by sudden load changes.

Additionally, Gil-González [28] proposed a methodology to identify the ideal bus locations for D-STATCOM installation in radial distribution networks, aiming to minimize power loss and enhance voltage magnitude. In the study of Shunmugham Vanaja et al. [29], an experiment was conducted to validate a Wind Energy Conversion System combined with a PV-fed modular STATCOM connected to a nonlinear load. A refined second-order generalized integrator with a fuzzy logic controller was successfully employed to regulate the output power. The findings demonstrated enhanced power quality and improved voltage regulation within the system.

Marzo et al. [30] conducted an in-depth investigation into the Delta-configured Cascaded H-Bridge (DCHB) topology as a promising solution for STATCOM applications, particularly in scenarios characterized by unbalanced voltage and/or current conditions. The study emphasized the necessity of injecting zero-sequence current to maintain the balance of the dc-link capacitor voltage, a critical factor for the reliable operation of the system. Additionally, the study did not extensively address the potential impact of non-idealities and practical considerations such as component tolerances and thermal effects, which can significantly influence the performance of the control strategies in practical applications.

Halder et al. [31] devised a tailored Hamiltonian functional, constructed from the system's parameters, to optimize the desired performance index. The Hamiltonian function method, known for its robustness in dealing with nonlinear systems, was applied to the STATCOM controller design to achieve superior transient stability performance. However, the practical implementation of the Hamiltonian function-based controller poses challenges, including the need for precise system parameter identification and the computational intensity of real-time optimization.

In a recent study, Imtiaz et al. [32] explored the optimization of STATCOM positioning using advanced optimization algorithms, specifically particle swarm optimization (PSO), the artificial hummingbird algorithm (AHA), and a novel hybrid method that combines both PSO and AHA. The primary objective of this approach was to enhance low-voltage ride-through (LVRT) capabilities, minimize generation losses during grid faults, and reduce oscillations following disturbances by effectively managing reactive power flow between the point of common coupling and the microgrid. As matter of fact, the implementation of such advanced algorithms in practical settings could face challenges related to computational demands and real-time adaptability.

STATCOMs are critical devices in enhancing power quality in distribution systems, and there is an ongoing tendency to optimize their performance to support additional ancillary services effectively. Implementation of a multilayer discrete noise-eliminating second order generalized integrator (MDNESOGI) is proposed by Nallaiyagounder et al. [33] to regulate the quasi-impedance source inverter (qZSI)-STATCOM. This approach aims to facilitate effective power interchange with the electrical network. As compared to the conventional second-order generalized integrator, the MDNESOGI shows improved performance in rejecting DC offset, which is particularly valuable during abnormal grid operations or system malfunctions. Moreover, the study did not extensively evaluate the long-term stability and robustness of the MDNESOGI under varying grid conditions and prolonged operation. The impact of integrating this advanced control strategy on the overall system cost and complexity was also not addressed. Furthermore, the study did not explore the integration of renewable energy resources with the distribution systems, which is an increasingly important aspect of modern power grid enhancements.

According to the study conducted by Sousa et al. [34], the integration process involves designing and implementing control strategies that can effectively manage the operation of modular multilevel converter (MMC)-based STATCOMs in medium voltage applications. MMCs offer several advantages, such as improved voltage quality and modularity, but they also introduce significant control complexities. One of the key challenges is accurately computing the gain of the controllers to ensure stable and efficient operation. Despite the potential benefits, the integration of MMCs into medium voltage STATCOMs is not without its drawbacks. The control algorithms required for MMCs are inherently complex, necessitating advanced computational resources and precise tuning. Furthermore, the study did not extensively address the practical implementation challenges, such as the impact of component tolerances and thermal management, which can affect the reliability and efficiency of MMC-based STATCOMs in real-world applications.

On the other hand, a limited number of researchers have undertaken comprehensive investigations into the intricacies surrounding the simulation and implementation of FACTS devices into the Iraqi power network. Recent studies [35-37] integrated STATCOM into the Iraqi power system to evaluate its practicality. Based on the continuation power flow (CPF) method, Khalaf et al. [35] examined potential locations of STATCOM within the 400 kV Iraqi national super grid to enhance its stability. The study identified node 20 to be a unique optimal position having a capacity of 700 MVA. Similarly, Al-Rubayi and Eesee [36] utilized particle swarm optimization to find the optimal siting and parameters setting of STATCOM within the whole Iraqi super grid. Interestingly, the study contradicts the previous study in the sense that it found multiple points of optimal insertion namely, buses 15, 21, 22, and 24.

Although the aforementioned studies exhibit a significant contribution to the field of power system, particularly in the context of nations facing formidable challenges within their power sectors, exemplified by Iraq, yet, comprehensive research endeavors exploring the implementation of STATCOM devices for power quality enhancement within regional power systems at a level of 132 kV is obviously scarce. To fill this gap, the study sheds light on the critical role of such devices in ameliorating pressing issues pertaining to high voltage power transmission of Diyala within the Iraqi Central Region National Grid (ICRNG). Clearly, this empirical validation of incorporating STATCOM devices underscores the potential of such interventions to mitigate operational inefficiencies and bolster grid resilience, offering practical implications for enhancing the reliability and performance of electrical power systems in analogous contexts globally.

3. CASE STUDY AND METHODOLOGY

Iraq is a war-torn middle eastern country that is facing multifaceted challenges in their power sector, particularly pertaining to power transmission and quality. Central to the discussion is the ICRNG, serving as a pivotal nexus catering to densely populated urban areas including Baghdad, Diyala, Anbar, and Wasit. Within this context, the electricity demand within the Diyala Governorate emerges as a focal point, constituting a significant portion of the overall load on the ICRNG. However, the persistent challenge of overloading has inflicted recurrent equipment malfunctions and electricity outages within the region, compounded by technical intricacies such as power quality fluctuations and synchronization loss. Of paramount concern is the risk of voltage breakdown stemming from imbalances between active and reactive power or the inadequacy of requisite reactive support from associated devices. Beyond the immediate ramifications of overloads, the sustained strain on the electrical power system precipitates instability and thermal stress, potentially culminating in widespread blackouts.

The electrical infrastructure of Iraq comprises high-voltage transmission lines operating at 132 kV and extra high voltage of 400 kV. The modeled national network within the Diyala region comprises 8 substations, featuring a total of 11 bus bars and 13 lines rated at 132 kV, satisfying a total load of 734 MW and 262 MVar. The public utility responsible for Diyala contends with persistent overloading issues, culminating in frequent equipment malfunctions and electricity outages within the region. Furthermore, technical challenges, including fluctuations in power quality and synchronization loss, exacerbate the situation.

The configuration of these bus bars is as follows: the first bus bar functions as the slack bus, the eleventh serves as the generator bus, while the remaining bus bars operate as load buses, as illustrated in Figure 3. Additionally, Table 1 and Table 2 furnish comprehensive real data pertaining to the power network of Diyala city, for emulation purposes, with B denoting line half susceptance. For the purpose of this investigation, MATLAB R2020a was utilized to configure the test system, followed by the execution of load flow analysis utilizing the Newton-Raphson (NR) method for the designated case study.

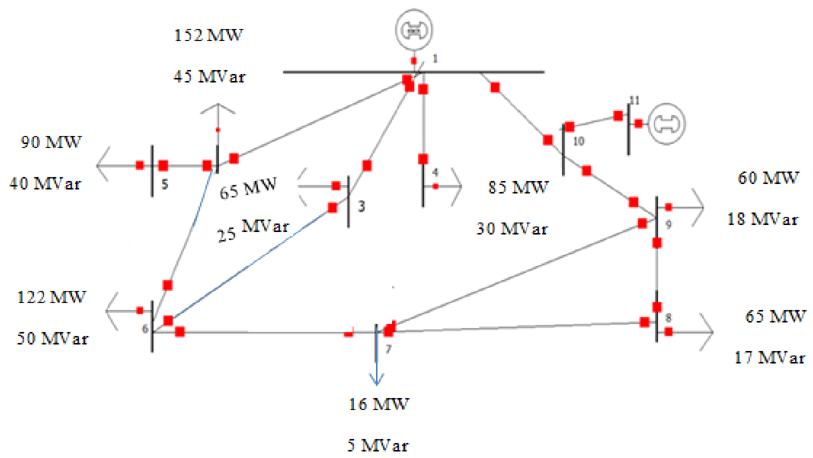

Figure 3. Diyala's 132 kV simulated transmission grid

Table 1. Network data of Diyala city

No.	Sending Bus	Receiving Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	1	2	0.0044	0.0196	0.0041
2	1	3	0.0406	0.1739	0.0349
3	1	4	0.0028	0.0156	0.0074
4	2	5	0.0155	0.0352	0.0064
5	3	6	0.0372	0.1596	0.032
6	6	7	0.0879	0.1782	0.0313
7	7	8	0.0528	0.2263	0.0454
8	9	10	0.0356	0.1525	0.0306
9	11	10	0.0064	0.0274	0.0055
10	10	1	0.0317	0.1358	0.2729
11	7	9	0.0164	0.0703	0.0141
12	9	8	0.0267	0.1143	0.0229
13	2	6	0.0155	0.0352	0.0064

The network was analyzed based on 100 MVA reference rating. Furthermore, the methodology pertaining to the installation of STATCOMs is delineated in the form of a flowchart, as depicted in Figure 4. It is worth pointing out that no optimization technique is imposed for siting the STATCOM devices into the studied power system; yet, localizing STATCOM equipment was adopted depending upon the optimal voltage state and loss minimization achieved for the whole system.

Table 2. Bus data of Diyala ring transmission grid

Bus No.	Bus Name	Active Load (MW)	Reactive Load (MVAr)	Type
1	Diyala	0	0	Slack
2	W. Baquba	152	45	Load
3	Baladruz	65	25	Load
4	Khalis	85	30	Load
5	S. Baquba	90	40	Load
6	E. Baquba	122	50	Load
7	Himreen	16	5	Load
8	Khanaqeen	65	17	Load
9	Muqdadya	60	25	Load
10	Hemreen	58	13	Load
11	Mansorya	21	12	Gen.

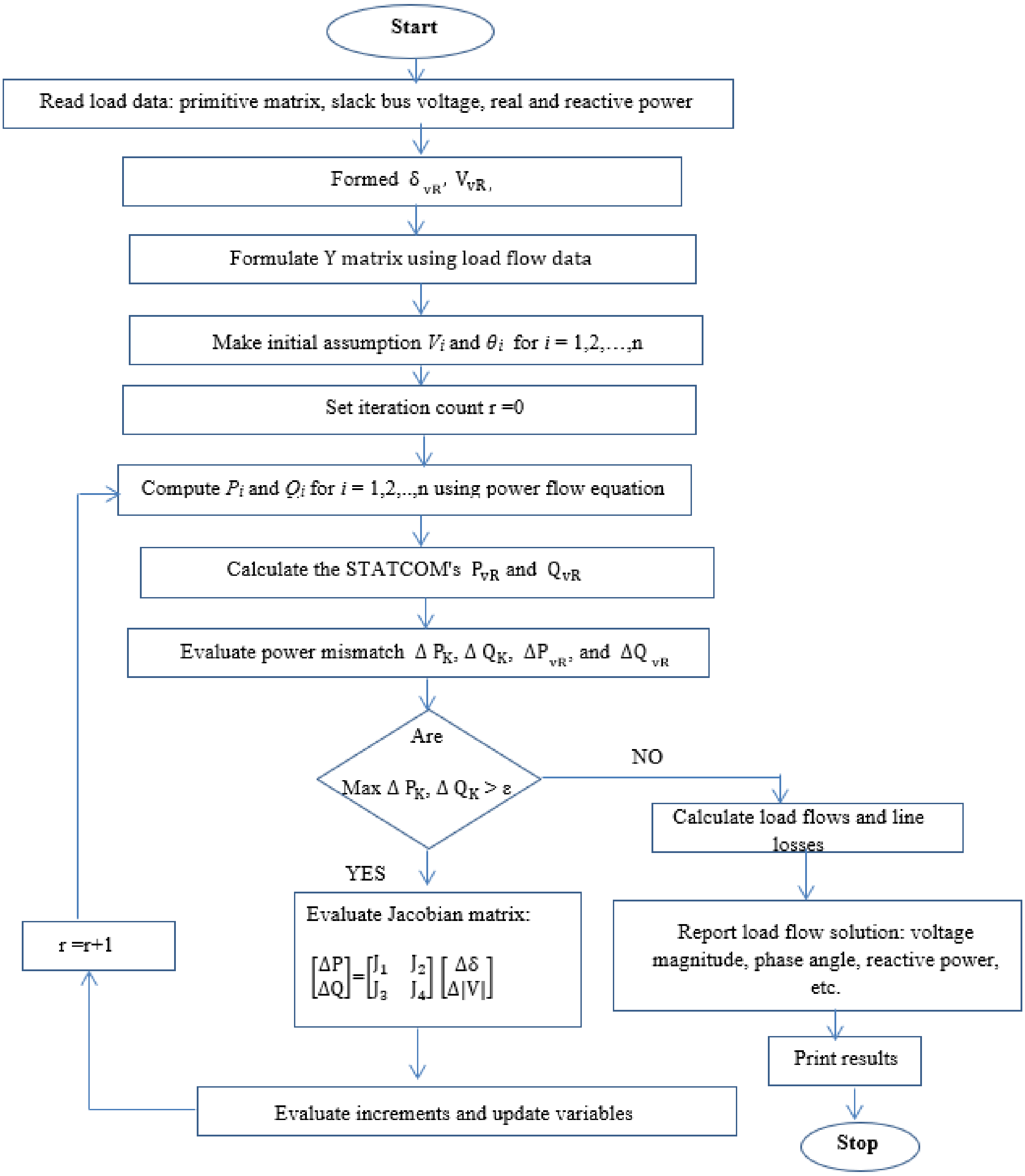

Figure 4. Flowchart algorithm for NR power flow with STATCOM integration

4. RESULTS AND ANALYSIS

In this section, the power quality state of the simulated Diyala high voltage transmission system is evaluated in terms of the voltage profile, as well as the active and reactive power loss, under two conditions: without the integration of a STATCOM device and with the inclusion of a STATCOM device. The effectiveness of the STATACOM is examined at three voltage scenarios the transmission grid may experience: under voltage of 125 kV, normal operation scenario of 132 kV, and over voltage scenario specified at 140 kV.

4.1 Voltage profile

The deployment of the STATCOM has been strategically executed at three distinct bus locations within the system, specifically buses 7, 8, and 9. This selection was predicated on their considerable distance from the power source and the notable losses incurred in the transmission lines connected to these stations. However, a comprehensive assessment of voltage levels spanning all nodes within the network was undertaken. The initial analysis of the system was conducted under a condition characterized by below-normal voltage.

Figure 5 indicates that bus 8 exhibits the most diminished voltage magnitude, registering at 0.74 per unit (p.u.). Following the insertion of the STATCOM at bus 8, a deliberate injection of reactive power into the system ensued. This proactive measure was aimed at counterbalancing the voltage drop experienced over the affected buses, thereby effectuating a stabilization of their voltage magnitude to 1 p.u. Noteworthy is the overarching influence exerted by the STATCOM, extending beyond the immediate vicinity of bus

8 to positively impact the voltage levels of several other buses—namely, buses 2, 3, 5, 6, 7, 9, 10, and 11. The examination of the test system extended to an overvoltage scenario, wherein an overvoltage event of 140 kV was considered. In such circumstances, a discernible voltage increase was observed at busbar 4, attributed to its proximity to the primary voltage source. Notably, the high voltage reading recorded at busbar 4 (1.053 per unit) prompted the Static Synchronous Compensator (STATCOM) to absorb reactive power from the system, thereby mitigating the voltages to 1 per unit, as depicted in Table 3.

Regardless of whether the voltage exceeds or falls below 1 per unit, the STATCOM consistently regulates it to this standardized level. Furthermore, the assessment of the test system under rated voltage conditions, specifically at 132 kV, was conducted. Figure 6 illustrates those buses 7, 8, and 9 exhibited diminished voltage magnitudes in per unit. However, following the installation of the STATCOM device at bus 9, notable improvements in voltage levels across the busbars were observed, converging towards a value close to 1 per unit.

Noteworthy is the extension of the STATCOM's impact beyond busbar 9 to encompass other buses within the network, thus demonstrating its efficacy in voltage regulation and system-wide enhancement.

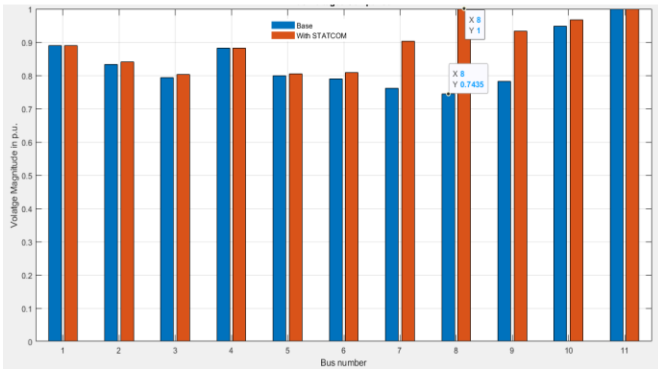

Figure 5. Bus voltage comparison without and with STATCOM at node 8, for under voltage scenario

Table 3. Voltage profile with and without STATCOM at node 4, for over-voltage scenario

Bus No.	Voltage Profile Without STATCOM						Voltage Profile with STATCOM					
	Voltage Mag.	Angle Degree	Load		Generation		Voltage Mag.	Angle Degree	Load		Generation	
			MW	MVar	MW	MVar			MW	MVar	MW	MVar
1	1.060	0.000	0.0	0.0	0.0	0.0	1.060	0.000	0.0	0.0	0.0	0.0
2	1.015	0.074	152.0	45.0	0.0	0.0	1.011	0.074	152.0	45.0	0.0	0.0
3	0.983	0.119	65.0	25.0	0.0	0.0	0.977	0.118	65.0	25.0	0.0	0.0
4	1.053	0.011	85.0	30.0	0.0	0.0	1.000	0.002	85.0	30.0	0.0	0.0
5	0.986	0.100	90.0	40.0	0.0	0.0	0.982	0.100	90.0	40.0	0.0	0.0
6	0.975	0.137	122.0	50.0	0.0	0.0	0.964	0.135	122.0	50.0	0.0	0.0
7	0.915	0.285	16.0	5.0	0.0	0.0	0.898	0.286	16.0	5.0	0.0	0.0
8	0.892	0.358	65.0	17.0	0.0	0.0	0.874	0.363	65.0	17.0	0.0	0.0
9	0.918	0.308	60.0	18.0	0.0	0.0	0.900	0.311	60.0	18.0	0.0	0.0
10	1.010	0.202	58.0	13.0	0.0	0.0	0.993	0.201	58.0	13.0	0.0	0.0
11	1.020	0.210	21.0	12.0	0.0	0.0	1.000	0.209	21.0	12.0	0.0	0.0

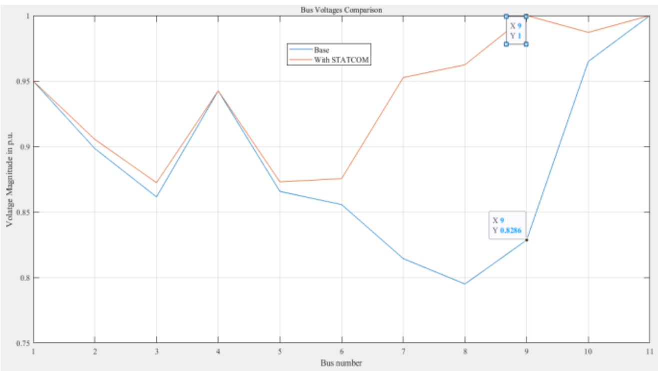

Figure 6. Bus voltage comparison without and with STATCOM at node 9, for normal voltage scenario

4.2 Active and reactive power loss

Table 4 provides a comparative analysis of line active and reactive power losses under-voltage conditions (125 kV), both with and without the implementation of STATCOM at bus 9. The findings elucidate significant improvements resulting from the introduction of the STATCOM. Upon integrating the STATCOM at bus 9, noteworthy reductions in total active power loss are observed, declining from 53.3 MW to 49.3 MW which represents a reduction by 7.5%. Concurrently, there is a substantial decrease in total reactive power loss, diminishing from 110.7 MVar to 80.08 MVar, representing a reduction by 27.66%. Moreover, the analysis reveals that the deployment of the STATCOM precipitates reductions in both active and reactive power losses across the majority of other lines within the system. This observation underscores the efficacy of STATCOM integration in ameliorating power losses and enhancing system efficiency thus power transfer capability under conditions of under-voltage operation.

Table 5 presents the power flow losses under overvoltage conditions (140 kV), both without and with the implementation of STATCOM at bus 9. Upon the integration of the STATCOM, notable improvement in system performance is observed. Post-STATCOM integration implies a substantial reduction in total real power loss, decreasing from 39.737 MW to 34.949 MW, providing an addition economic benefit. Additionally, there is a significant decrease in total reactive power loss, plummeting from 41.355 MVar to 17.352 MVar. These findings demonstrate the efficacy of STATCOM deployment in mitigating power losses, both real and reactive ones, thereby enhancing system efficiency and stability amidst overvoltage conditions.

In the context of normal-voltage operation, an optimal placement for the installation of STATCOM device is identified at bus 9, resulting in minimal power system loss. Table 6 tabulates a comparative analysis of line flow and losses with and without a STATCOM at bus 9 under normal voltage conditions, specifically at 132 kV. The data clearly demonstrates that integrating a STATCOM at node 9 yields a discernible reduction in total active power loss, decreasing from 46.134 MW to 41.415 MW. Furthermore, there is a notable decrease in total reactive power loss, diminishing from 75.710 MVar to just 47.613 MVar i.e., 37.11% minimization is achieved.

These findings underscore the efficacy of deploying a STATCOM in mitigating power losses, both in terms of active and reactive power, thereby accentuating its potential to optimize system efficiency and performance under normal-voltage conditions.

To validate the effectiveness of the developed program, load flow analysis of the IEEE 30-bus power system with the inclusion of STATCOM device has been conducted and the results are exhibited in Table 7. It is obvious that the integration of static compensators at node 26 has improved the voltage profile of the whole system. Interestingly, the outcome conforms to the results obtained by the load flow study provided by MathWorks [38].

Table 4. Line loss without and with STATCOM at bus 9 for under-voltage scenario

Line Loss Without STATCOM				With STATCOM	
From Bus	**To Bus**	**MW**	**MVar**	**MW**	**MVar**
1	2	11.70	51.42	10.49	46.03
1	3	3.56	9.54	3.22	7.99
1	4	0.25	0.10	0.25	0.10
2	5	2.02	3.60	1.97	3.47
3	6	0.07	-4.31	0.07	-4.59
6	7	7.69	11.52	9.73	14.54
7	8	0.62	-2.53	0.39	-6.55
9	10	5.89	20.68	2.89	6.32
11	10	1.26	4.37	0.20	-0.20
10	1	11.18	-1.03	11.59	-1.56
7	9	0.24	-0.68	1.07	1.89
9	8	0.84	0.95	0.66	-1.59
2	6	7.97	17.10	6.72	14.23
Total loss		**53.30**	**110.73**	**49.26**	**80.08**

Table 5. Line loss without and with STATCOM at bus 9 for over-voltage scenario

Line Loss Without STATCOM				With STATCOM	
From Bus	**To Bus**	**MW**	**MVar**	**MW**	**MVar**
1	2	9.19	40.06	8.56	37.26
1	3	2.76	4.55	2.59	3.77
1	4	0.20	-0.51	0.20	-0.51
2	5	1.55	2.25	1.54	2.21
3	6	0.07	-5.76	0.05	-5.97
6	7	6.63	8.13	5.57	5.32
7	8	0.51	-4.54	0.36	-7.02
9	10	3.49	9.63	2.03	2.41
11	10	0.15	-0.45	0.04	-0.99
10	1	8.09	-22.71	7.60	-26.89
7	9	0.14	-1.55	0.34	-1.31
9	8	0.59	-0.89	0.53	-2.19
2	6	6.35	13.15	5.55	11.30
Total loss		**39.74**	**41.36**	**34.95**	**17.35**

Table 6. Line loss without and with STATCOM at bus 9 for normal-voltage scenario

Line Loss Without STATCOM				With STATCOM	
From Bus	**To Bus**	**MW**	**MVar**	**MW**	**MVar**
1	2	10.47	45.86	9.52	41.60
1	3	3.17	7.16	2.90	5.96
1	4	0.23	-0.18	0.23	-0.18
2	5	1.78	2.94	1.75	2.85
3	6	0.07	-4.94	0.05	-5.22
6	7	7.26	10.12	7.47	9.60
7	8	0.57	-3.35	0.38	-6.78
9	10	4.61	14.89	2.48	4.52
11	10	0.53	1.22	0.06	-0.85
10	1	9.35	-12.24	9.20	-14.90
7	9	0.18	-1.11	0.68	0.19
9	8	0.72	0.11	0.59	-1.89
2	6	7.20	15.24	6.11	12.73
Total loss		**46.13**	**75.71**	**41.42**	**47.61**

Table 7. Load flow results of IEEE 30-bus with and without STATCOM by the developed program

	Voltage Profile Without STATCOM						Voltage Profile With STATCOM					
Bus No.	**Voltage mag.**	**Angle degree**	**Load**		**Generation**		**Voltage mag.**	**Angle degree**	**Load**		**Generation**	
			MW	MVar	MW	MVar			MW	MVar	MW	MVar
1	1.060	0.000	0.000	0.000	0.000	0.000	1.060	0.000	0.000	0.000	0.000	0.000
2	1.010	0.076	21.700	12700	40.0	48.822	1.000	0.058	21.700	12700	40.0	48.822
3	0.997	0.117	2.400	1.200	0.000	0.000	1.110	0.118	2.400	1.200	0.000	0.000
4	0.984	0.142	7.600	1.600	0.000	0.000	1.060	0.141	7.600	1.600	0.000	0.000
5	0.980	0.234	94.200	19.000	0.000	35.975	1.000	0.150	94.200	19.000	0.000	35.975
6	0.981	0.168	0.000	0.000	0.000	0.000	1.040	0.183	0.000	0.000	0.000	0.000
7	0.972	0.205	22.800	10.900	0.000	0.000	1.016	0.152	22.800	10.900	0.000	0.000
8	0.980	0.182	30.000	30.000	0.000	30.826	1.000	0.167	30.000	30.000	0.000	30.826
9	0.998	0.188	0.000	0.000	30.0	0.000	1.024	0.207	0.000	0.000	30.00	0.000
10	0.995	0.232	5.800	2.000	0.000	0.000	1.018	0.137	5.800	2.000	0.000	0.000
11	1.000	0.188	0.000	0.000	0.000	16.119	1.000	0.167	0.000	0.000	0.000	16.119
12	1.001	0.233	11.200	7.500	0.000	0.000	1.044	0.218	11.200	7.500	0.000	0.000
13	1.000	0.233	0.000	0.000	0.000	10.423	1.000	0.167	0.000	0.000	0.000	10.423
14	0.986	0.249	6.200	1.600	0.000	0.000	1.027	0.232	6.200	1.600	0.000	0.000
15	0.982	0.249	8.200	2.500	0.000	0.000	1.022	0.230	8.200	2.500	0.000	0.000
16	0.991	0.238	3.500	1.800	0.000	0.000	1.026	0.219	3.500	1.800	0.000	0.000
17	0.988	0.238	9.000	5.800	0.000	0.000	1.015	0.215	9.000	5.800	0.000	0.000
18	0.974	0.256	3.200	0.900	0.000	0.000	1.008	0.235	3.200	0.900	0.000	0.000
19	0.972	0.257	9.500	3.400	0.000	0.000	1.003	0.234	9.500	3.400	0.000	0.000
20	0.977	0.252	2.200	0.700	0.000	0.000	1.006	0.228	2.200	0.700	0.000	0.000
21	0.982	0.242	17.500	11.200	0.000	0.000	1.006	0.217	17.500	11.200	0.000	0.000
22	0.983	0.242	0.000	0.000	0.000	0.000	1.007	0.217	0.000	0.000	0.000	0.000

23	0.974	0.254	3.200	1.600	0.000	0.000	1.008	0.232	3.200	1.600	0.000	0.000
24	0.971	0.255	8.700	6.700	0.000	0.000	0.998	0.229	8.700	6.700	0.000	0.000
25	0.973	0.254	0.000	0.000	0.000	0.000	1.010	0.229	0.000	0.000	0.000	0.000
26	0.955	0.262	3.500	2.300	0.000	0.000	0.992	0.237	3.500	2.300	0.000	0.000
27	0.984	0.249	0.000	0.000	0.000	0.000	1.026	0.225	0.000	0.000	0.000	0.000
28	0.979	0.180	0.000	0.000	0.000	0.000	1.028	0.1528	0.000	0.000	0.000	0.000
29	0.963	0.272	2.400	0.900	0.000	0.000	1.006	0.246	2.400	0.900	0.000	0.000
30	0.951	0.289	10.600	1.900	0.000	0.000	0.995	0.232	10.600	1.900	0.000	0.000

5. CONCLUSION AND FUTURE WORK

STATCOMs emerge as pivotal components in the pursuit of a resilient and sustainable energy landscape. Their capacity to provide dynamic voltage support and reactive power compensation facilitates the maintenance of stable and dependable electricity provision within an evolving energy paradigm. This study introduces a technical investigation on STATCOM integration to provide resilience of a vulnerable power transmission network. Within the context of implementing STATCOM within the Diyala electrical grid, three distinct scenarios were explored: stable voltage condition labeled at 132 kV, corresponding to the nominal voltage level of the Diyala high-voltage transmission network, under-voltage at 125 kV, and over-voltage which is specified at 140 kV. The findings illuminate the profound impact of STATCOM integration on system performance across these scenarios. Obviously, the incorporation of STATCOM, particularly at remote bus locations is shown to bolster and sustain the voltage profile of the entire network, maintaining it close to the standardized 1 p.u. level. Furthermore, a notable reduction in both active and reactive power losses within the entire transmission lines is observed, indicative of the enhanced power transfer capability afforded by STATCOM intervention.

Regarding voltage profile enhancement, the installation of the Static Synchronous Compensator at bus 8 facilitates the injection of reactive power into the system, effectively counteracting voltage drops across affected buses and thereby stabilizing their voltage magnitudes to 1 per unit (p.u.). Importantly, the influence of the STATCOM transcends the confines of bus 8, manifesting in a positive modulation of voltages at other pertinent buses—namely, buses 2, 3, 5, 6, 7, 9, 10, and 11. Additionally, the test system underwent scrutiny under conditions of overvoltage. In the event of the transmission network experiencing an overvoltage condition reaching 140 kV, a discernible increase in voltage is discerned at node 4 due to its proximity to the primary voltage source. In response to the elevated voltage recorded at busbar 4 (1.053 p.u.), the STATCOM promptly absorbs reactive power from the system, thus effecting a reduction in voltages to 1 p.u. Notably, irrespective of whether the voltage surpasses or falls short of the 1 p.u. threshold, the STATCOM meticulously regulates it to 1 p.u., thereby underscoring its efficacy in voltage control and system stability maintenance.

The investigation of this paper provides comprehensive line flow and loss data comparisons under below-voltage condition (125 kV), both with and without the integration of STATCOM at bus 9. The results reveal significant improvements attributable to the STATCOM insertion. Upon the installation of the STATCOM at bus 9, a conspicuous reduction in total active power loss is attained, decreasing from 53.3 MW to 49.3 MW i.e., a reduction by 7.5%. Correspondingly, there is a notable decrease in total reactive power loss, plummeting from 110.7 MVar to 80.08 MVar, which represents a reduction by 27.66%. Moreover, the analysis discerns noteworthy reductions in both active and reactive power losses across the majority of other lines within the system. This empirical evidence demonstrates the efficacy of integrating a STATCOM at bus 9 in ameliorating overall power losses, thus underscoring its potential to enhance system efficiency and stability under conditions of under-voltage.

In the event of overvoltage (140 kV), the analysis encompasses the evaluation of power flow and losses with and without the implementation of STATCOM at bus 9. The results reveal substantial improvements following the integration of the STATCOM. Upon STATCOM integration, a notable reduction in total real power loss is observed, decreasing from 39.737 MW to 34.949 MW. Similarly, a significant decrease in total reactive power loss is achieved, plummeting from 41.355 MVar to 17.352 MVar. During normal operating condition, the results underscore the pronounced impact of STATCOM implementation at node 9, elucidating a reduction in total active power loss from 46.134 MW to 41.415 MW, alongside a decrease in total reactive power loss from 75.710 MVar to 47.613 MVar, i.e., 37.11% minimization is obtained. These findings prove the practicality of STATCOM installation at node 9 being the optimal location leading to a mitigation in power losses, both real and reactive, thereby affirming its potential to bolster system efficiency and stability.

This study is of significance, being provides a practical solution for other cases sharing a similar geopolitical environment. However, one crucial area for future work is the detailed analysis of harmonics introduced by STATCOMs in fragile power transmission systems. Indeed, harmonics can adversely affect power quality and system stability, leading to increased losses and potential damage to equipment. Future research can focus on developing advanced harmonic mitigation techniques and control strategies to minimize the impact of harmonics. Power losses in transmission systems are also a critical concern, particularly in systems with high levels of reactive power compensation. Future studies could aim to quantify the power losses associated with STATCOM operations and explore methods to minimize them. Supporting the grid with renewable energy resources is an essential aspect of modern power systems. Thus, future work can explore the integration of STATCOMs with renewable energy sources such as solar systems, wind turbines, and fuel cells. Finally, economics of STATCOM as compared to other FACTS devices and policy/regulatory initiatives supporting the implementation of such equipment could also be of interest for future research.

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