J. Electrical Systems 20-10s (2024): 6166-6175

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Performance Evaluation of a FACTS Controller for Power Quality Improvement Based on Standard IEEE 16 Bus

Journal of Electrical Systems

Abstract: - FACTS systems have the ability to rapidly modify transmission line parameters such as impedance, phase, and voltage in order to provide a rapid controller for responding to transmission or distribution. This particular kind of FACTS has the capability to be integrated into the transmission line IDVR, as well as other commonly used systems such as unified power controllers (UPFCs), in order to harness the available energy from the system. The FACTS have undergone inspection inside the power system domain. The applied FACTS family offers several benefits, including improved system stability, enhanced loading capacity of transmission systems, improved power quality, and increased efficiency of low generating cost. In the event of a fault, an increased amount of reactive power is required from the system in order to rectify the fault and restore the system to a stable state. This study investigates the simulation results and analysis of the IEEE 16-bus system, both with and without an IDVR unit, during a single line fault and a three lines fault. The 16-bus system is represented using Simulink blocks. The objective of this study is to advocate for the implementation of an IDVR model to enhance power quality.

Keywords: Component, Power Quality, IDVR, FACTS Devices, Single line fault, Three line fault, IEEE 16 Bus System.

I. INTRODUCTION

Power quality (PQ) is crucial for the successful operation of various applications, including production and information technology. It also plays a significant role in ensuring the efficient control and automation of technology systems. As a result, PQ has gained significant attention from industrial and commercial consumers[1] . Additionally, it is essential to protect the power system from adverse weather conditions in order to prevent electricity overload.To regulate multiple parameters of a transmission line [2]. FACTS provide features that enhance the transmission line by optimizing the utilization of current resources, improving the reliability of the line, maintaining the stability of the grid during transient events, and increasing the quality of power supply for sensitive manufacturing processes[3] .Implementing multiple Flexible AC Transmission Systems (FACTS) can effectively mitigate various Power Quality (PQ) concerns. The recent implementation of Flexible AC Transmission Systems (FACTS) has improved the efficient utilization of power system resources. The fundamental implication of FACTS relies on the utilization of high power electronics to control active power, reactive power, and voltage in transmission lines[5,6].A IDVR unit is a parallel reactive compensation device that is inserted into transmission and distribution systems. It is based on Voltage Source Converters (VSCs) which consist of self-commutated switching units. IDVR devices use commutated switches such as thyristors to inject or absorb reactive power in order to compensate for the transmission system located between the load and generators [7].

The power quality issues, such as voltage sag and swell, can be mitigated by implementing specialized power devices. A customized power device is utilized to rectify the issues encountered by end-user loads in relation to voltage sags and voltage swells. Electrical distribution network breakdowns are responsible for around 90% of customer outages on average. Due to the increasing consumer demand for power supply reliability, it is important to enhance the reliability of the system. One of the primary issues addressed here is the cause of Voltage sag[8]. Power distribution systems should ideally deliver a continuous and uninterrupted supply of energy to consumers, with a stable sinusoidal voltage at the proper magnitude level and frequency. An example of such a controller is the Interline Dynamic Voltage Restrorer (IDVR), which is considered the most efficient and effective contemporary bespoke power device utilized in power distribution networks. The appeal of this product lies in its reduced cost, smaller size, and its rapid dynamic responsiveness to disturbances[9].The advantages of bespoke power devices are enumerated below. 1. Power flow can be enhanced through the utilization of operational margins and decreased through the implementation of quick controllability. 2. The power transmission capacity of power lines can be enhanced in order to establish thermal stability. 3. Enhancing the stability limit leads to an improvement in the

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dynamic security of the system, resulting in a reduction in the occurrence of blackouts caused by cascading outages.
4. These controllers can effectively address the issue of voltage fluctuations, specifically over voltages.

II.OPTIMAL SIZING AND PLACEMENT MODEL OF IDVRS

A. The simplified model of IDVRs

IDVR was modeled as a variable voltage source and mitigation performance at the neighborhood of target bus was investigated. These IDVRs consists of a transformers, filters and AC/AC conversion circuits. It extracts energy from the power system by power conversion circuit and doesn't provide both real and reactive power compensation. It adopts in-phase compensation strategy and the boost voltage is injected in phase with the dipped voltage. When a voltage sag occurs, IDVR can inject an appropriate voltage U_{com} in phase with upstream side voltage U . The sag can be compensated and the load voltage U_{sen} can be maintained at an acceptable level. Since the power loss of most IDVR is very low, the power loss is ignored to simplify calculation. Therefore, the IDVR is modeled as an ideal voltage source to restore voltage magnitude during sag[10].

B. Objective function

To obtain an effective allocation of IDVRs, the following objective function of minimizing the total investment of IDVRs is adopted

$$\min f = min \sum_{x=1}^{N} C(S_x) \tag{1}$$

where N is the total number of IDVRs, x S is the capacity of the xth IDVR and its total cost is represented by C(Sx) . The total investment is decided by the number and the cost of the devices.The cost of the DVR was often derived from multiplying the capacity by unit price.In fact, the price per kVA of DVR is not a constant. It will decrease as the capacity of IDVR increases. A continuous function p(S) was proposed to describe the unit price of IDVR. Therefore, the cost of DVR, C(S) can be defined as equation (2)

$$C(S) = p(S)S \tag{2}$$

The continuous function p(S) reflects the fact that the price per kVA of IDVR changes with capacity and contributes to obtain practical schemes. Moreover, the sizing and placement for DVRs becomes a continuous optimization problem. Such a problem is easier to solve than discrete optimization problems, since many discrete optimization algorithms generate a sequence of continuous sub problems[11].

C. Constraints

There are capacity constraint and voltage constraint in the optimization model. The capacity of DVR depends on its maximum restorable voltage. The capacity constraint can be described as equation (3), and the power loss of IDVR is ignored.

$$S_x \geq U_{com}^{x} I_x \tag{3}$$

Where I_x is the output current of the x^{th} IDVR and U_{com}^{x} is the maximum restorable voltage of the x^{th} IDVR.The output current I_x of the x^{th} IDVR should satisfy the need of downstream loads and can be described as equation (4).

$$I_x = \frac{\sum_{y=1}^{T} a_{yx} S_L^y}{U_n} \tag{4}$$

where S_L^y is the capacity of the y^{th} sensitive load, U_n is the nominal voltage, T is the total number of sensitive loads. A related coefficient a_{yx} is introduced to indicate the topological relationship among IDVR positions and sensitive load. If the x^{th} IDVR locates on the upstream of the y^{th} sensitive load, 1 a_{yx} = 1 otherwise, a_{yx} = 0 .

To ensure normal operation of equipment, the voltage of sensitive load after compensation during voltage sags should be maintained within a permissible voltage range. The voltage constraint can be described in equation (5).

$$U_{min}^{y} \leq U_{sen}^{y} \leq U_{max}^{y} \tag{5}$$

Where U_{sen}^{y} is the voltage of the y^{th} load after compensation, U_{min}^{y} and U_{max}^{y} minimum and maximum permissible voltage of the y^{th} sensitive load. The voltage of the y^{th} load after compensation, U_{sen}^{y} supposed to be the sum of its dipped voltage and output voltage of related IDVRs.

$$U_{sen}^{y} = U^{y} + \sum_{x=1}^{N} a_{yx}\, U_{com}^{x} \qquad (6)$$

Where U^y is the voltage of the y^{th} load to be compensated, usually the voltage during sag, U_{com}^{x} is the output voltage of the x^{th} IDVR. If multiple sensitive customers are on one branch and a IDVR is selected for the whole branch, the output voltage of the IDVR should satisfy customers' maximum demand for compensation on the branch. The output voltage constraint of IDVR can be described in equation (7).

$$U_{com}^{x} \geq \max\{a_{yx}(U_{sen}^{y} - U^{y})\}\,(y = 1,2,\ldots,K) \qquad (7)$$

However, not all customers expect to alleviate all voltage sags for high cost of mitigating some infrequent deep sags. To achieve a tradeoff between investment and mitigation effectiveness, the voltage to be compensated should consider customers demand [11].

III. INTERLINE DYNAMIC VOLTAGE RESTORER

The IDVR system comprises multiple DVRs located in separate feeders, all connected to a shared dc link. The IDVR system is connected to two separate feeds that originate from two grid substations[10].These two feeders may have either the same or different voltage levels. Feeder 1 adjusts for a decrease in voltage, while feeder 2 runs in power-flow control mode to restore the energy storage of the dc-link, which has been reduced by the real power consumed by the IDVR operating in voltage-sag compensation mode. The propagation of voltage sags resulting from faults in the power system is influenced by various parameters, including voltage level, fault current, transformer in the propagation path, and their connection layout[11]. Voltage sags in a transmission system are more prone to spreading over a greater electrical distance compared to a distribution system. Because of these reasons, the two feeders of the IDVR system in Figure 1 are linked to two separate grid substations. It is logical to expect that the voltage drop in Feeder 1 would have a smaller effect on Feeder 2. Thus, the generating transmission system that supplies power to the two feeders can be regarded as two separate and independent sources.

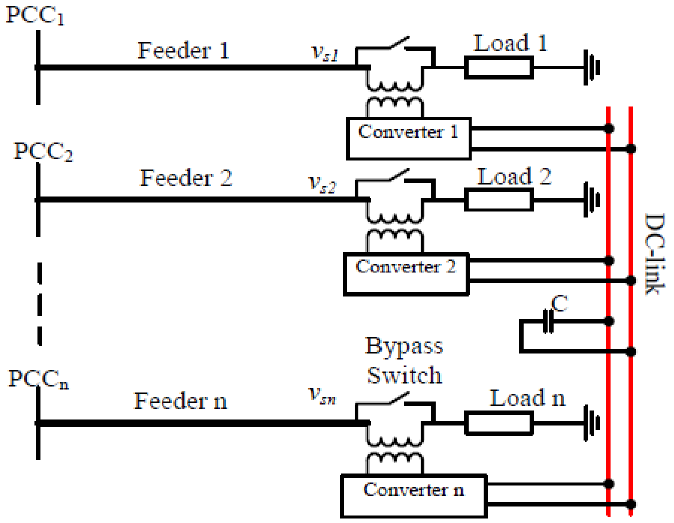

Figure 1.Single line diagram of multiline distribution system.

The IDVR is primarily composed of the following components: an Injection transformer, DC charging unit, Storage Devices, Voltage Source Converter (VSC), Harmonic filter, Control and Protection system[12] .IDVR can be operated in three distinct operation modes, namely Bypass mode, Standby mode, and Active mode. The bypass mode allows the IDVR to be disconnected in situations of high load currents and short circuits. In this mode, the IDVR is unable to apply a voltage injection to enhance the quality of electricity. In standby mode, the supply voltages are operating at their designated levels and the IDVR (Interline Dynamic Voltage Restorer) is prepared to counteract any voltage drop[13]. While in standby mode, the IDVR enhances the load voltage. In active mode, the IDVR detects a voltage dip and compensates by injecting the necessary voltage.

IV. METHODS OF VOLTAGE INJECTION IN IDVR

The voltage injection methods of an IDVR primarily rely on power ratings and various load circumstances. Various techniques exist for measuring IDVR voltage. The two methods of compensation are pre-sag compensation and in-phase compensation. In the pre-sag situation, compensation is applied to the load voltage in order to align it with the tracked supply voltage. This technique ensures that the load voltage remains uninterrupted, although it typically necessitates a greater rating for the IDVR [14].In an Interline Dynamic Voltage Restorer (IDVR), voltage injection is essential for preserving voltage stability among linked power lines. The principal techniques of voltage injection employed in IDVR systems are outlined below. The IDVR utilizes VSIs to inject regulated voltage directly into the power lines.

These inverters may adaptively modify their output in accordance with the voltage demands of the associated lines.The IDVR can stabilize voltage levels by regulating active power. This strategy entails modulating the power output to equilibrate demand and supply, particularly during disruptions. The IDVR can offer reactive power assistance to the lines, aiding in the rectification of voltage fluctuations[15]. By modulating the reactive power output, the system may either improve or reduce voltage as required. The IDVR can introduce a phase-shifted voltage to mitigate voltage losses or sags. This approach is very efficacious in improving problems resulting from imbalanced loads. The integration of energy storage technologies, such as batteries, enables the IDVR to retain surplus energy and use it as required, offering both real and reactive power assistance[16]. This approach enables inverters to dynamically distribute the load, ensuring voltage stability across several lines by modulating their outputs according to system conditions.

This sophisticated method forecasts future voltage requirements and modifies injection tactics accordingly, enhancing performance. In an IDVR system with numerous converters, coordinated control algorithms synchronize voltage injection across various lines, mitigating conflicts and guaranteeing overall stability. The IDVR may be engineered to deliver voltage assistance during disturbances, preserving stability until normal circumstances are reinstated. These strategies jointly guarantee that the IDVR proficiently sustains voltage quality across interconnected networks, adapting to demand variations and other dynamic grid changes. Prior to the occurrence of a sag, the voltage across the system $\mathbf{V_S}$ is equal to the voltage across the load $\mathbf{V_L}$ which is equal to the initial voltage$\mathbf{V_0}$. Here, the supply voltage is denoted as $\mathbf{V_S}$, the load voltage is denoted as $\mathbf{V_L}$, and the pre-sag voltage is denoted as $\mathbf{V_0}$. The voltage sag causes a decrease in the magnitude of the supplied voltage to $\mathbf{V_{SL}}$. The phase angle of the power supply may also undergo a shift[17].The DVR applies a voltage, denoted as $\mathbf{V_{C1}}$, in order to maintain the load voltage ($\mathbf{V_L = V_{SL} + V_{C1}}$)at $\mathbf{V_0}$.Pre-sag voltage, referring to both its magnitude and phase. It is asserted that certain loads are responsive to sudden changes in phase and it is imperative to address both the phase jumps and the voltage sags.Phase adjustment ensures that the voltage injected by the IVDFC voltage is always synchronized with the supply, regardless of the load current and pre-sag voltage$\mathbf{V_0}$. This control approach yields the least value of the injected voltage[18]. For loads that are not affected by phase jumps, this control method allows for the most efficient use of the voltage rating of the IVDFC. The power needs for the IVDFC are non-zero for this technique.

V. DISPLACEMENT POWER FACTOR

The displacement power factor is defined as the ratio of the active fundamental power (P) divided by the fundamental apparent power (S). The reactive power Q provided to the inductive device is the vector difference between the real power and the apparent power[19]. The displacement factor is the cosine of the angle between the fundamental components of the phase voltage and phase current, which is calculated by measuring the displacement angle. In an Interline Dynamic Voltage Restorer (IDVR), voltage injection is essential for maintaining voltage stability across linked lines, whereas a Displacement Factor Controller (DFC) is dedicated to optimising the power factor and managing reactive power. Here is an in-depth examination of both facets. The IDVR employs Voltage Source Inverters (VSIs) to introduce a regulated voltage into the power lines. This may rectify voltage sags, swells, or variations by increasing or decreasing voltage as required[20]. The IDVR promptly adjusts to voltage circumstances in real-time, delivering immediate voltage assistance to the affected lines. This guarantees that voltage levels stay within permissible ranges. The IDVR enhances voltage profiles by injecting reactive power, particularly during peak demand or fault scenarios. This functionality aids in voltage stabilisation and enhances overall power quality[21]. The IDVR may oversee several linked lines, supplying electricity where it is most required according to real-time data and control algorithms.

The integration of energy storage devices enables the IDVR to deliver stored energy at crucial periods, therefore improving its capacity to address voltage fluctuations and offering supplementary support. The Displacement Factor Controller seeks to enhance the displacement factor (the cosine of the phase angle between voltage and current), hence improving overall power quality by improving reactive power usage. The DFC regulates the inverter's reactive power output to maintain the displacement factor within specified limits. This entails real-time modifications contingent upon load circumstances. The DFC can be combined with the IDVR to offer additional voltage assistance.

The IDVR concentrates on voltage stabilization, whilst the DF guarantees an ideal power factor, hence minimizing losses and enhancing efficiency[22]. The IDVR and DFC can collaborate to improve overall system efficacy. Improving electrical system power quality is possible with the use of a Displacement Factor Controller (DFC) and an Interline Dynamic Voltage Restorer (IDVR). Here are the functions of each part and the advantages they provide when used together.In the event of power outages or disruptions, the IDVR can either inject or absorb electricity. A number of linked lines can be dynamically supported by it. Rapid and adaptable voltage support is provided by Voltage Source Inverters (VSIs), which also provide consistent voltage levels across all buses.The IDVR may transfer power across many lines, providing efficient voltage support where it is most required, by linking them.The DFC's primary goal is to maximise the displacement factor, which is defined as the angle dissimilarity between the current and voltage waveforms. Reactive power output is controlled, which fixes the power factor.Load efficiency and loss reduction are both improved by adjusting the reactive power injected into or absorbed from the system[23].The DFC enhances the capacity of the current infrastructure and decreases line losses by enhancing the power factor.Complementing the IDVR's functions, keeping the displacement factor ideal helps stabilise voltage levels.While the DFC optimises the power factor, the IDVR focusses on preserving voltage levels. They work in tandem to enhance power quality by fixing problems with voltage and reactive power.

This combination improves system resilience against disturbances and decreases equipment failure chance by minimising voltage sags and rectifying power factor concerns.Maintaining power supply stability and quality is made possible by real-time modifications made possible by the integrated system's capacity to adapt rapidly to changing conditions[24]. The IDVR and DFC can help stabilise the grid by controlling reactive power and voltage variations, which will be more important as distributed generation and renewable energy sources grow in popularity.Lower energy losses in the transmission and distribution networks are a direct result of better power quality, which in turn makes the operation more efficient and cost-effective.An effective method for improving power quality is to strategically employ a Displacement Factor Controller in conjunction with an Interline Dynamic Voltage Restorer. This comprehensive method contributes to the development of a more dependable, efficient, and robust power system by concurrently tackling voltage fluctuations and optimising power factor[25].

The IDVR mitigates voltage fluctuations, while the DFC regulates the displacement factor, hence providing voltage stability and optimal power flow. Through the coordination of their activities, the IDVR and DFC can reduce energy losses, optimise voltage profiles, and augment the dependability of the whole power system[26]. This comprehensive strategy fosters the development of a robust power network that proficiently resolves voltage and power quality challenges, resulting in a more stable and efficient grid.

$$S^2 = \sqrt{P^2 + Q^2} \tag{8}$$

$$\emptyset = \tan^{-1}\left(\frac{Q}{P}\right) \tag{9}$$

$$\text{Displacement Factor} = \cos\emptyset = P/S \tag{10}$$

The Real and Reactive power is given by

$$\mathrm{P_{total}} = V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\theta_v - \theta_i) \tag{11}$$

$$\mathrm{Q_{total}} = \sum_{h=1}^{\infty} V_h I_h \sin(\theta_v - \theta_i) \tag{12}$$

Apparent Power is given by

$$S_{total} = \sqrt{\sum_{h=0}^{\infty} (I_h - V_h)^2} \tag{13}$$

$$\text{Therefore Displacement factor} = \sqrt{S_{total}^2 - P_{total}^2 - Q_{total}^2} \tag{14}$$

VI. POWER SYSTEM FOR IEEE 16-BUS MODEL UNDER STUDY

This work presents the implementation of the FACTS (Flexible Alternating Current Transmission System) device in the IEEE 16-bus system with the purpose of improving power quality [13,14]. The IDVR is an essential element for contemporary power systems, particularly in intricate networks such as a 16-bus system. IDVRs boost voltage stability and improve overall system performance through the integration of modern control techniques and power electronics.

In MATLAB modeling, meticulous attention to the configuration, control strategy, and disturbance reaction is crucial for precise simulations and valuable insights. The Interline Dynamic Voltage Regulator (IDVR) is a sophisticated control system designed to enhance voltage stability and quality in power systems. In a 16-bus model, the IDVR regulates voltage levels across several buses, ensuring they stay within acceptable parameters during normal operations and fault scenarios. Examine the voltage profiles, current flows, and the operational efficacy of the IDVR under both normal and fault situations. This entails analysing the system's performance under several contingency situations to assess the power system's resilience and dependability. Examining the efficacy of voltage regulation techniques, such as the use of IDVR or alternative voltage support technologies can reveal their influence on system performance[13]. Time-domain simulations facilitate the analysis of the system's dynamic response to diverse perturbations and control schemes throughout time. The study examines the system performance under single line fault and three line fault scenarios, both with and without IDVR.The IEEE 16-bus standard is depicted in Figure (2). It consists of five synchronous machines, three of which is Interline Dynamic Voltage Restorer used solely for reactive power supply. There are a total of 11 loads, with a combined power of 280 megawatts and a reactive power of 85 megawatts

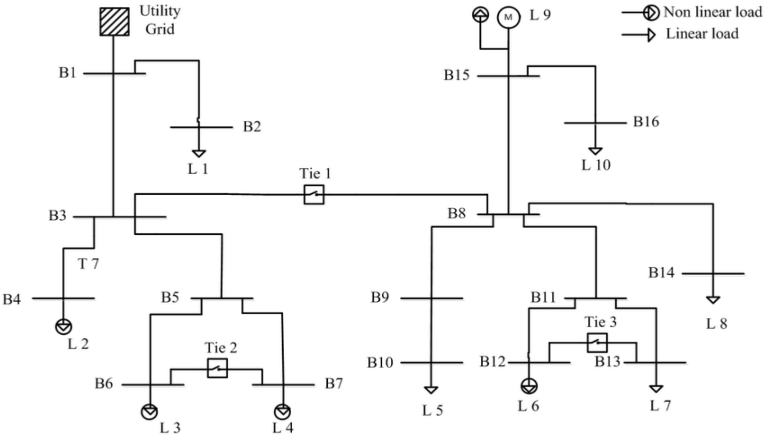

Figure 2: Standard of IEEE 16-bus system with IDVR

VII.RESULTS AND DISCUSSIONS

When the system is operating with and without IVDFC, a single-line fault and three-line fault are introduced, with a fault resistance of 0.001Ω.

A.Case Study (1): Single-line fault

The system's performance, both with and without IVDFC, is illustrated in this case study.The case study displays the voltage response during a single-line fault at bus 1, 2, 3, 4, 5, 8, 9, 13, 14, 15, and 16. It has been observed that the voltage response overshoot is improved when using IDVR compared to the system without IDVR. Table (I) presents the performance specifications with and without IDVR when a single-line fault disturbance occurs, specifically in terms of overshoot.

Under overshoot											
BUS NUMBER	(1)	(2)	(3)	(4)	(5)	(8)	(9)	(13)	(14)	(15)	(16)
Without IDVR Voltage (p.u)	1.5x10-3	2.5	1.5	1.1	3.72	1.05	1.01	1.4	1.28	1.15	1.2
With IDVR Voltage (p.u)	1.2x10-3	2.0	1.2	1.05	2.3	1.1	1.1	1.3	1.34	1.3	1.2

Table 1: Performance of IVDFC in the event of a single line fault disruption.

B.Case Study 2: Three-line fault

The system's performance, with and without IDVR, is shown in case study 2 in relation to the voltage response during a three-line fault at buses 1, 2, 3, 4, 5, 8, 9, 13, 14, 15, and 16. It has been observed that the inclusion of IDVR results in an improved response in terms of voltage, specifically in reducing overshoot compared to a system without IDVR. Table (II) presents a summary of the performance specifications with and without IDVR during three line fault disturbances.

Under overshoot											
BUS NUMBER	(1)	(2)	(3)	(4)	(5)	(8)	(9)	(13)	(14)	(15)	(16)
Without IDVR Voltage (p.u)	$1.14x10^{-6}$	1.4	1.3	1.4	1.10	1.10	1.0	1.1	1.3	1.4	1.5
With IDVR Voltage (p.u)	$1.06x10^{-6}$	1.1	1.0	1.3	1.0	1.2	1.1	1.0	1.15	1.14	1.31

Table 2: Performance specifications when a three-line fault disturbance occurs.

VIII.CONCLUSION

The results demonstrate that the system equipped with the IDVR device significantly enhances power quality and reduces overshoot in comparison to the system without the IDVR. Hence, the findings demonstrate that the system equipped with IDVR exhibits robustness in handling parameter variations. The IEEE 16-bus system is simulated and modeled using an IDVR device, to increase power quality (PQ).The examination of the IEEE 16-bus system using an Interline Dynamic Voltage Restorer (IDVR) reveals substantial enhancements in power quality, voltage stability, and system dependability. The IDVR efficiently alleviates voltage sags and swells, maintaining voltage levels within permissible ranges during disturbances. This capacity is essential for safeguarding sensitive equipment and ensuring service continuity. This efficiency enhances overall system performance and capacity. The IDVR's capacity to react instantaneously to disruptions improves the resilience of the IEEE 16-bus system. This flexibility is crucial for contemporary power systems encountering more intricate and changeable demands. As the power grid adapts to integrate additional renewable energy sources, the IDVR can be pivotal in regulating the resultant fluctuation and ensuring system stability. The deployment of an IDVR in the IEEE 16-bus architecture demonstrates its efficacy as a strategic remedy for contemporary power system issues. The findings highlight the significance of sophisticated voltage control technology in improving the resilience, efficiency, and dependability of electrical networks. Ongoing research and development in this domain will further enhance sustainable and stable power system operations. The system model is analyzed and evaluated using the Matlab program and numerical simulations. The simulations focus on fault scenarios, namely single-line faults and three-line faults, and examine the voltage response with and without IDVR. The system's power with IDVR is favored because to its efficiency and rapid fault recovery, which restores the system to a stable state. This is in contrast to systems that lack FACTS devices. The system details for IEEE 16-bus is specified in tables 3,4 and 5

Bus number	Load	
	P(MW)	Q(MW)
1	0	0
2	20.6	11.5
3	92.3	18
4	46.5	-2.8
5	6.5	1.4
6	10.5	6.8
7	0	0
8	0	0
9	27.4	14.7
10	8.5	4.9
11	3.2	1.5
12	5.8	1.4
13	12.8	4.9
14	13.5	6
15	14.8	4.9
16	15.2	4.1

Table 3: IEEE 16 Bus data Load details

Buses	Resistance (p.u)	Reactance (p.u)	Line charging(p.u)	Rating (p.u)	Tap ratio
1 and 2	0.0185	0.039	0.046	250	1.5
1and 5	0.047	0.205	0.041	150	1.5
2 and 3	0.035	0.177	0.042	150	1.5
2 and 4	0.044	0.156	0.0213	150	1.5
2 and 5	0.046	0.156	0.031	150	1.5
3 and 4	0.055	0.152	0.0321	150	1.5
4 and 5	0.010	0.152	0.0114	150	0.945
4 and 7	0.01	0.034	0.01	150	0.94
4 and 9	0.01	0.110	0.01	150	0.92
5 and 6	0.01	0.4471	0.01	150	1.5
6 and 11	0.075	0.141	0.01	150	1.5
6 and 12	0.0111	0.183	0.01	150	1.5
6 and 13	0.0551	0.147	0.01	150	1.5
7 and 8	0.01	0.1201	0.01	150	1.5
7 and 9	0.01	0.1641	0.01	150	1.5
9 and 10	0.022	0.10111	0.01	150	1.5
9 and 14	0.117	0.0079	0.01	150	1.5
10 and 11	0.0712	0.2121	0.01	150	1.5
12 and 13	0.212	0.1832	0.01	150	1.5
13 and 14	0.167	0.1882	0.01	150	1.5
15 and 16	0.168	0.242	0.01	150	1.5

Table 4: IEEE 16 Bus Data Transmission Line Characteristics

Bus No.	P_G min (MW)	P_G max (MW)	Q_G min (Mvar).	Q_G max (Mvar).	Cost Coefficients		
					A	b	C
1	15	260	15	260	0.0027	1.50	0.1
2	25	150	-20	60	0.0145	1.35	0.1
3	20	120	0	50	0.0325	1.10	0.1
6	15	140	-8	30	0.0067	3.10	0.1
8	15	45	-8	30	0.0236	3.10	0.1
10	15	50	-7	20	0.0136	2.15	0.1

Table 5 IEEE 16 bus data Cost Coefficient and Generation limits

$$\text{Generating Cost} = \sum_{i=1}^{N_G} a_i\, P_{Gi}^2 + b_i P_{Gi} + c_i \quad \$/\text{hr}$$

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