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Modification of Dynamic Voltage Restorer for Improved Power Quality in Industrial Electrical Networks

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Abstract

Reliable power quality is a crucial factor in maintaining continuity and operational efficiency in industrial power grids. Power quality disturbances such as voltage sags, voltage swells, and interruptions can cause equipment damage, decreased productivity, and increased operational costs. Dynamic Voltage Restorers (DVRs) have proven effective in addressing voltage disturbances, but conventional devices have limitations, specifically, they are only able to compensate for voltage drops up to approximately 30% of the nominal value and cannot address interruption disturbances. This study proposes a modified DVR with the addition of an energy storage system and an adaptive control algorithm to expand the voltage compensation capabilities, including under extreme voltage sags and interruption disturbances. Simulation results show that the modified DVR is able to maintain load voltages close to the nominal value under various disturbance scenarios, thereby significantly improving the power quality and reliability of the industrial power grid.

Keywords: *PLTH, NPC, COE*

Abstrak

Kualitas daya yang andal merupakan faktor krusial dalam menjaga kontinuitas dan efisiensi operasional di jaringan listrik industri. Gangguan kualitas daya seperti penurunan tegangan, lonjakan tegangan, dan interupsi dapat menyebabkan kerusakan peralatan, penurunan produktivitas, dan peningkatan biaya operasional. Dynamic Voltage Restorer (DVR) telah terbukti efektif dalam mengatasi gangguan tegangan, tetapi perangkat konvensional memiliki keterbatasan, khususnya, mereka hanya mampu mengkompensasi penurunan tegangan hingga sekitar 30% dari nilai nominal dan tidak dapat mengatasi gangguan interupsi. Studi ini mengusulkan DVR yang dimodifikasi dengan penambahan sistem penyimpanan energi dan algoritma kontrol adaptif untuk memperluas kemampuan kompensasi tegangan, termasuk di bawah penurunan tegangan ekstrem dan gangguan interupsi. Hasil simulasi menunjukkan bahwa DVR yang dimodifikasi mampu mempertahankan tegangan beban mendekati nilai nominal di bawah berbagai skenario gangguan, sehingga secara signifikan meningkatkan kualitas daya dan keandalan jaringan listrik industri.

Kata kunci: PLTH, NPC, COE

I. INTRODUCTION

In electric power systems, power quality is a key determinant of energy supply reliability. As society and industry increasingly rely on electronic equipment and automated processes, tolerance for power outages decreases. Poor power quality can lead to financial losses, reduce operational efficiency, and impact user comfort and safety. These disruptions can originate in the generation, transmission, and distribution systems and are triggered by varying and increasingly complex load conditions.

Poor power quality can cause significant disruptions to operations in the industrial, commercial, and residential sectors. In the manufacturing industry, for example, voltage sags can cause production interruptions and potentially damage equipment and machinery. In the commercial and residential sectors, power quality disturbances can damage electronic equipment and reduce user comfort. Therefore, maintaining stable and reliable power quality is a top priority in electricity distribution system management [1]. The two most common and impactful power quality issues are voltage sags and voltage swells. Voltage sags typically occur due to short circuits, motor starting, or the sudden connection of large loads. Meanwhile, voltage swells are generally caused by switching capacitor banks or shedding large loads. Both types of disturbances can cause damage to electronic equipment, reduce equipment lifespan, and hinder the normal operation of the electrical system [2].

Good electrical power quality plays a crucial role in mining operations, particularly in ensuring the reliability of equipment such as conveyors, pumps, drilling rigs, and other heavy machinery that rely heavily on a stable power supply [3]. Power quality disturbances, such as unstable voltage, harmonics, or voltage fluctuations, not only have the potential to damage equipment and increase maintenance costs, but can also reduce energy efficiency, disrupt productivity, and increase operational costs [5]-[7]. From a safety perspective, equipment that is not functioning optimally due to power problems can endanger workers and disrupt electrical-based security and monitoring systems [4]. Furthermore, poor power quality can trigger sudden shutdowns, cause financial losses, and even increase emissions because equipment is operating below optimal efficiency [6], [8]. Therefore, maintaining stable and reliable power quality is key to ensuring safe, efficient, productive, and environmentally friendly mining operations.

Conventional methods for improving power quality, such as installing capacitors and reactors, generally have limitations in effectively handling dynamic load variations and temporary disturbances. These limitations include low flexibility and a slow response time to maintain real-time voltage stability [5]. One modern solution that has been widely used is the Dynamic Voltage Restorer (DVR), a Flexible AC Transmission Systems (FACTS) device designed to address power quality issues, particularly voltage sags and voltage swells [9]. The DVR works by injecting the necessary voltage into the system so that the voltage on the load side can be maintained at nominal conditions. The main advantage of the DVR lies in its ability to respond quickly to voltage changes, thus providing an effective and efficient solution in improving power quality [10]. However, conventional DVRs are generally only able to handle voltage drops of up to 30% of the nominal voltage. In the event of interruption disturbances that occur on feeders supplying electricity to customers, conventional DVRs are unable to provide compensation. Therefore, modifications to the DVR are needed to be able to handle voltage drops of more than 30% and provide protection against interruption disturbances.

Modifications to the DVR are a strategic step to expand its ability to maintain continuity of power supply under various disturbance conditions. By adding energy storage features or integrating with an uninterruptible power supply (UPS) system, the DVR can maintain voltage supply even in the event of extreme voltage sags or even interruptions. Furthermore, the development of adaptive control algorithms allows the DVR to respond more quickly to voltage fluctuations and adjust compensation in real time according to load characteristics. This approach not only improves the DVR's performance in dealing with short-term disturbances but also provides more reliable protection for sensitive equipment in industrial and commercial environments. Thus, DVR modifications are expected to be a comprehensive solution for improving power quality while increasing the reliability of the electricity distribution system.

II. CONVNTIONAL OF DYNAMIC VOLTAGE RESTORER

A. *Sensitivity Curve*

Natural phenomena and limitations in energy generation, transportation, and distribution systems can cause electrical disturbances. These disturbances can be caused by maneuvers, damage, atmospheric phenomena, or the load on the power receiver, and can affect processes or services while causing economic losses to the company. Most industrial equipment meets the sensitivity curve defined by the IEEE 446 standard, as shown in Fig. 1, where the equipment operates normally as long as the voltage falls between the two curve limits, indicated by the light gray areas [11]. However, the voltage on the power grid does not always fall within these limits. Disturbances, represented by the dark gray areas, vary depending on their magnitude and duration. Disturbances cannot be completely eliminated, so customer facilities need to be adjusted to protect normal operations and minimize the disturbances that can enter the power grid. Typically, disturbances cause a voltage drop of -10% to -40% with a duration of 0–500 milliseconds, while serious disturbances can reach -60% if they last longer. A failure at the power source can trigger a series of interruptions caused by automatic reconnection to correct the fault. This series of interruptions often forces voltage-compensating equipment to operate for several seconds.

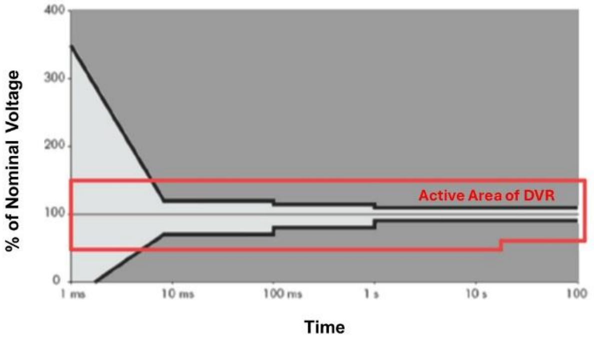

Fig. 1 Industrial equipment sensitivity curve [11]

B. *General DVR Operating Principle*

The diagram as shown in Fig. 2 is a block diagram of a Dynamic Voltage Restorer (DVR), a power electronics-based device used to protect the power system from voltage disturbances such as sags, swells, and flickers in the distribution network [12], [13]. The DVR works by injecting the appropriate voltage into the system to ensure that the load receives a stable, high-quality voltage.

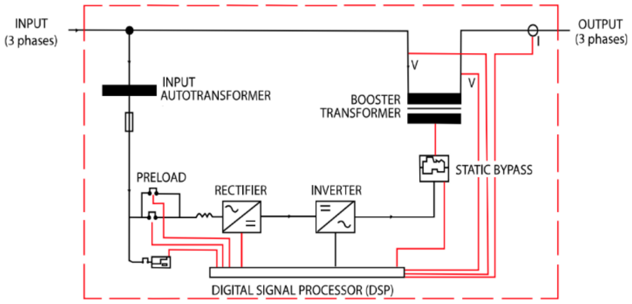

Fig. 2 Diagram block of DVR [11]

First, the system receives input from the three-phase network. This input voltage passes through an autotransformer, which adjusts the voltage level to meet the DVR's requirements. The signal then enters the preload and rectifier block, where the rectifier converts the AC voltage to DC for further processing. This DC voltage feeds the inverter, which converts the DC energy back into AC with the appropriate amplitude, frequency, and phase for compensation in the system.

Another important block is the booster transformer, which is used to inject the inverter's output voltage into the distribution line. This way, if a sag (voltage drop) or swell (voltage increase) occurs, the inverter generates a corrective voltage that is channeled through the booster transformer, maintaining a stable voltage on the load side. The booster transformer also provides isolation between the DVR and the main system.

In addition, there's a static bypass switch that allows power to flow directly through the DVR to the load in the event of a disturbance or failure in the DVR itself. The final component is the Digital Signal Processor (DSP), an intelligent controller that monitors system conditions, calculates compensation requirements, and regulates the operation of the rectifier, inverter, and static bypass so that the DVR can operate in real time with very fast response.

DVRs have proven effective in addressing sags, swells, and other power quality disturbances. However, the DVR's main weakness is its inability to address disturbances in the form of full voltage interruptions (momentary blackouts). This is due to the DVR's limited energy source. DVRs typically draw energy from the DC link (the output of a rectifier or from a temporary energy storage capacitor). This capacitor can only provide limited energy for a very short time. In the case of a total voltage interruption, the voltage supply from the network is completely lost, leaving the DVR without a voltage reference and sufficient additional energy to maintain power supply to the load. As a result, although the DVR can compensate for voltage drops of up to 30%, it cannot provide full energy like an Uninterruptible Power Supply (UPS).

C. *Mathematical model of DVR*

The mathematical model of voltage injection with the DVR system can be illustrated in Fig. 3. The system voltage source is denoted by Vth, which represents the Thevenin voltage of the power system. The source impedance is expressed as a combination of resistance R_{th} and reactance jX_{th}. The load current flowing is indicated by I_L, while the voltage at the load side is V_L. The load receives a complex power in the form of $PL+jQL$, which consists of active power (PL) and reactive power (Q_L). The total impedance and voltage can be expressed by the following equation:

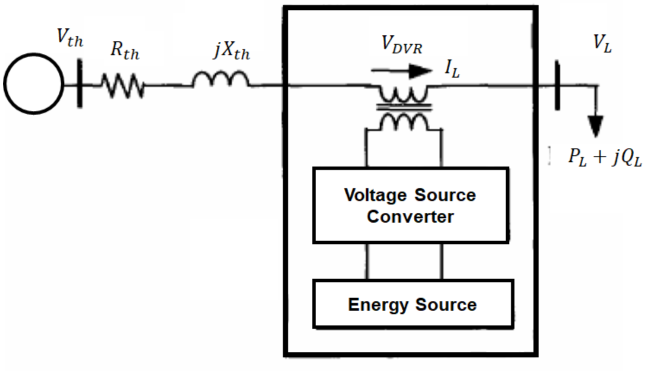

Fig. 3 Computation of Injected Voltage in DVR

$$Z_{th} = R_{th} + jX_{th} \tag{1}$$

$$V_{DVR} + V_{th} = V_L + Z_{th} I_L \tag{2}$$

If there is a decrease in load voltage (V_L), the DVR will inject a series voltage (V_{DVR}) through the injection transformer so that the desired load voltage V_L can be maintained. Therefore,

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{3}$$

$$I_L = \left[\frac{P_L + jQ_L}{V_L}\right]^* \tag{4}$$

When VL is considered as a reference, then

$$V_{DVR}\angle\alpha = V_L\angle 0^o + Z_{th} I_L \angle(\beta - \theta) - V_{th}\angle\delta \tag{5}$$

Where, α, β and δ are the angles of V_{DVR}, Z_{th} and V_{th} respectively and θ is the angle of the load power factor which is expressed by

$$\theta = tan^{-1}\left(\frac{Q_L}{P_L}\right) \tag{6}$$

The DVR power injection can be written as follows:

$$S_{DVR} = V_{DVI} I_{DVR} \tag{7}$$

III. DVR SYSTEM MODIFICATION

A Dynamic Voltage Restorer (DVR) is a device used in electric power systems to protect sensitive loads from power quality issues, such as voltage sags, voltage surges, and other temporary disturbances. DVRs work by injecting compensating voltage to prevent voltage variations from affecting the continuity of the power supply to critical loads. However, conventional DVRs are limited in handling very deep sags (below 30% of the nominal voltage) and momentary voltage interruptions. These conditions can cause damage to sensitive equipment because the DVR is unable to provide additional voltage quickly enough or in sufficient quantities.

To overcome these limitations, DVRs need to be modified to have faster response times and greater voltage injection capacity. This improvement can be achieved through advanced control technology and high-speed components. Furthermore, the integration of energy storage systems such as batteries or supercapacitors allows DVRs to provide voltage supply during temporary interruptions. With a more reliable design, the modified DVR is able to maintain power supply continuity and provide optimal protection for critical loads.

A. DVR System Modification Topology

The main circuit of the conventional DVR modification is shown in Fig. 4 which consists of a four-quadrant charger, supercapacitor, inverter, injection transformer, static switch, fail-safe bypass, and maintenance bypass. The static switch is connected between the main power supply and the protected load.

The modified DVR topology is essentially similar to a conventional DVR, but is equipped with energy storage technology in the form of a supercapacitor. The presence of a supercapacitor allows the DVR to have an energy reserve that can be immediately used in the event of a voltage disturbance, making it more effective in handling very deep sags and momentary interruptions. With this energy storage, the DVR becomes more reliable in maintaining power supply continuity and providing optimal protection for sensitive loads.

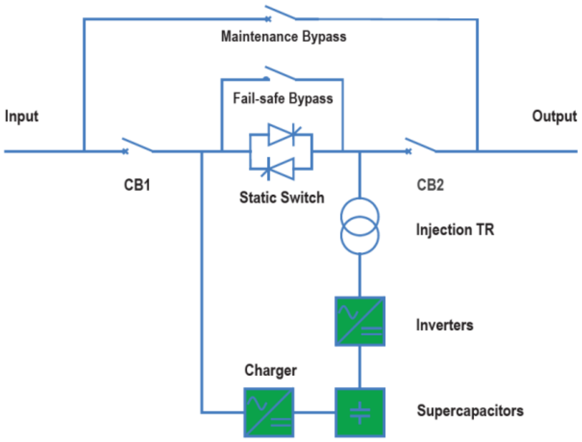

Fig. 4 Modified DVR system topology

Supercapacitors, or ultracapacitors, are high-capacity capacitors capable of storing 10 to 100 times more energy per unit volume or mass than electrolytic capacitors. Compared to batteries, supercapacitors can charge and discharge energy more quickly, have a much longer charge and discharge life cycle, and operate over a wider operating temperature range (-40°C to +65°C). From a safety standpoint, supercapacitors are superior because they are not susceptible to explosions due to overheating like batteries. These characteristics make supercapacitors ideal energy storage components in power quality protection applications, particularly in modified DVRs.

B. Working Principle of Modified DVR System

1) Standby State: When the grid voltage is within the normal range, the DVR remains in standby. In this state, the input and output circuit breakers CB1 and CB2 are closed, and the static switch is turned on (see Fig. 5). Power is supplied directly to the load through the static switch. Furthermore, the supercapacitor is at full power. The inverter is in hot backup mode and synchronized with the grid voltage in real time, allowing it to react immediately in the event of a voltage disturbance.

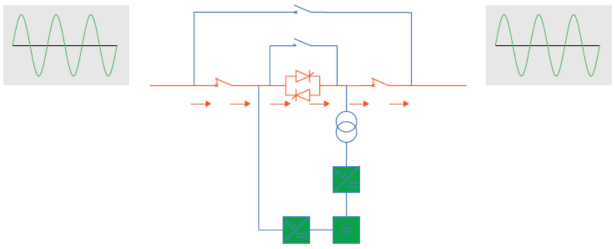

Fig. 5 Modified DVR system topology

2) Protection State: The DVR monitors the grid voltage in real time. If the grid voltage exceeds a predetermined range, the DVR immediately controls the static switch to open, and the protected load is completely isolated from the mains power. At the same time, the energy stored in the supercapacitor is converted to AC power and supplied to the protected load through an injection transformer (see Fig. 6). From the perspective of the protected load, the transition between mains power and inverse power is smooth, and the power supply to the load is uninterrupted, ensuring continuous operation.

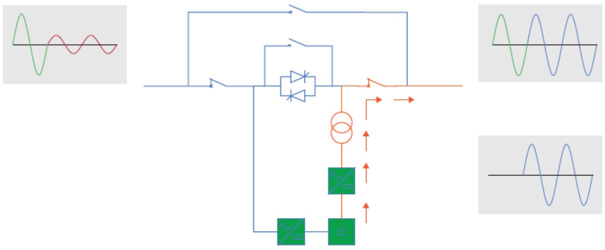

Fig. 6 Power flow in protection state

3) Recovery State: When the DVR monitors that the grid voltage has returned to normal, it will stop the inverter and turn on the static switch. This way, the output voltage returns to grid voltage, and the supercapacitor begins charging in preparation for the next protection phase (see Fig. 7).

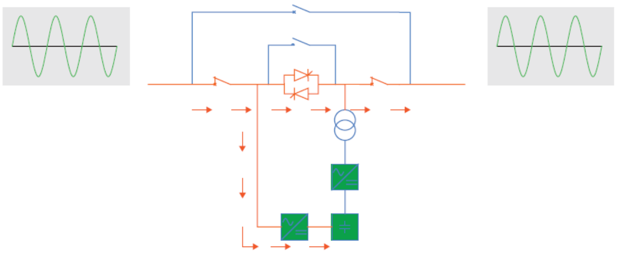

Fig. 7 Power flow in recovery state

4) Fail-Safe Bypass State: In the event of a catastrophic failure of the DVR, the fail-safe bypass will automatically bypass the static switch. Power will be supplied to the load directly through the bypass. In this state, the DVR will not respond to abnormal network voltage events (see Fig. 8).

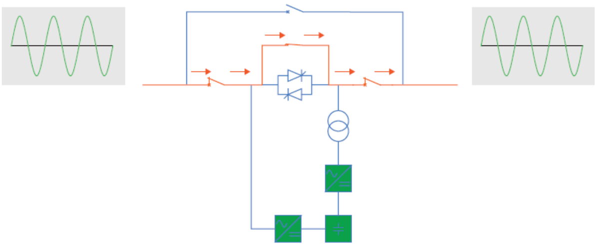

Fig. 8 Power flow in Fail-Safe Bypass State

IV. SIMULATION AND ANALYSIS

A. Existing Electrical System and Problem

The Single Line Diagram of the existing system considered in this paper is a system with Low Voltage Main Distribution Panel (LVMDP) is shown in Fig 9. The loads on the LVMDP are three Motor Crusher (MC) with a capacity of 590 kW, 550 kW, and 250 kW, respectively.

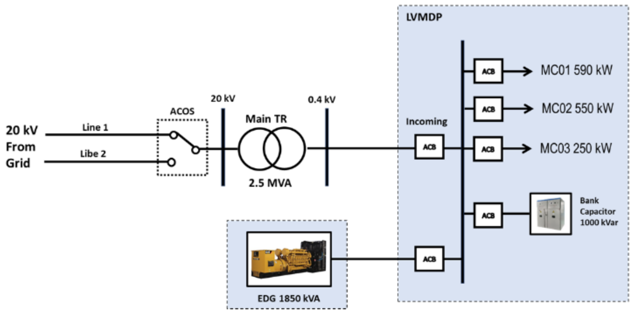

Fig. 9 Power flow in Fail-Safe Bypass State

The main issues leading to the failure of the electrical system, apart from voltage sags and swells, were:

- The transition of power supply from Feeder 1 to Feeder 2 (20 kV) through the Automatic Change Over Switch (ACOS), which caused a 300 ms outage and resulted in a complete shutdown of the electrical system and mining operations.
- The system operated at a low voltage of 400 V supplied by two 20 kV feeders. A voltage difference between the feeders (20.1 kV on Feeder 1 and 19.5 kV on Feeder 2) led to a voltage drop on the transformer's low-voltage side. When the voltage fell below 390 V, motor failures occurred.

B. Electrical System with Proposed DVR

As a solution to improve power reliability and quality, the installation of a modifiacation DVR is proposed. This device is capable of handling power quality disturbances such as sags, swells, and momentary interruptions by injecting voltage quickly and accurately, ensuring a stable and continuous power supply to critical equipment. The reconfiguration of the LVMDP-CPP electrical system is shown in Fig. 10. A 1750 kVA DVR with a 15-second supercapacitor is installed between the outgoing low-voltage 400 V transformer and the incoming ACB of the LVMDP. Additionally, a synchronization panel is placed on the outgoing Diesel Emergency Generator (DEG).

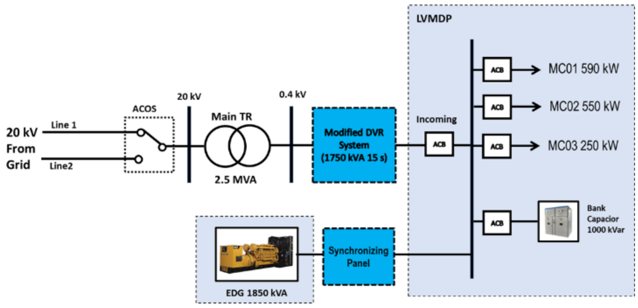

Fig. 10 Re-configuration of the electrical system with modified DVR

C. *Simulation Results*

To determine the effectiveness of the proposed DVR modifications in improving the reliability and stability of the electrical system, simulations and analyses were conducted using EMTDC's PSCAD software. This software enables detailed modeling of the electrical power system and simulation of various electrical phenomena, including voltage disturbances.

The electrical system was completely mapped into PSCAD, including relevant power sources, loads, and distribution elements. The modified DVR model was then integrated with the technical parameters specified. Simulations were conducted under several disturbance scenarios, including a 70% voltage sag, a 120% voltage swell, and a 300-millisecond interruption of one second duration, to evaluate the DVR's response in maintaining voltage stability.

1) Voltage Sag Disturbance: A voltage sag is a sudden, short-term drop in voltage. Simulations show that when a voltage sag occurs, the modified DVR can quickly detect the voltage drop and inject additional voltage to compensate. The simulation results show that the voltage on the load, which initially dropped to 70% of its nominal value, was successfully restored to normal levels in less than one cycle as shown in Fig 11. This ensures that equipment sensitive to voltage changes continues to operate normally without damage or malfunction.

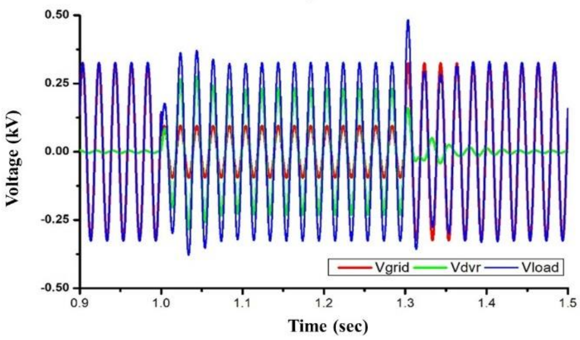

Fig. 11 Voltage profile during 70% voltage sag disturbance

2) Voltage Swell Disturbance: A voltage swell is a sudden increase in voltage that also lasts for a short time. In this scenario, the modified DVR functions by absorbing the excess voltage that occurs. Simulation results show that when a voltage swell occurs that reaches 120% of the nominal voltage, the DVR can reduce the voltage back to normal levels in a very short time. The voltage graph in Fig. 12 shows the DVR's rapid response in dampening the voltage increase, thereby protecting equipment from potential damage due to excess voltage.

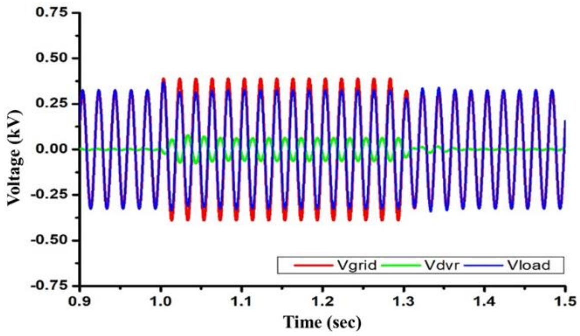

Fig. 12 Voltage profile during 120% voltage swell disturbance

3) Interruption: An interruption is a condition where the voltage suddenly disappears completely. In this simulation, a modified DVR is designed to provide backup voltage during the interruption. The simulation results show that the DVR is able to provide a stable backup voltage, so that the load continues to receive electricity even though the main source is interrupted. The voltage graph shown in Figure 13 shows that during the interruption period, the voltage at the load remains stable at the expected nominal value, ensuring the continuity of operation of critical equipment.

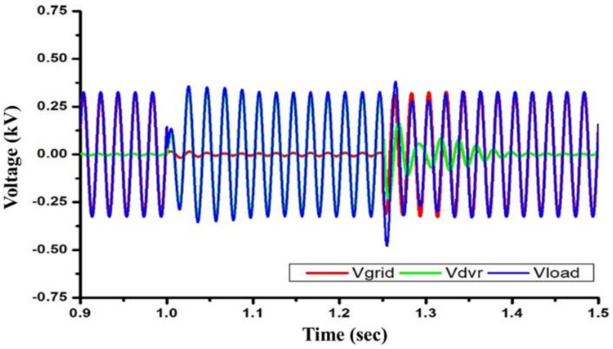

Fig. 13 Voltage profile during interruption disturbance

Overall, the simulation results show that the modified DVR is capable of providing a fast and effective response to various types of voltage disturbances. With the ability to compensate for voltage sags, dampen voltage swells, and provide backup voltage during interruption disturbances, the DVR provides significant protection to equipment. This not only improves the reliability of the electrical system but also reduces potential downtime and maintenance costs due to equipment failure. Therefore, implementing the modified DVR is a strategic step that supports efficient and reliable operational continuity.

V. CONCLUSIONS

After conducting an in-depth analysis and installing a modified Dynamic Voltage Restorer (DVR) on the electrical system under consideration, several conclusions can be drawn based on the identified problem formulation:

Voltage disturbances such as voltage sags, voltage swells, and interruptions significantly affect power quality in the power distribution system. These voltage fluctuations can cause damage to equipment, disrupt production processes, and increase operational costs due to downtime and repairs. The installation of the modified DVR demonstrates its effectiveness in maintaining voltage stability, thereby mitigating the negative impact of these disturbances.

Conventional DVRs have several drawbacks, including a slower response to sudden voltage changes, limitations in handling severe disturbances, and reliance on a system design that may not be optimal for all operational conditions. Furthermore, conventional DVRs may not be able to efficiently handle complex voltage disturbances, resulting in inadequate protection for sensitive equipment.

The design and implementation of the modified DVR involved improving the control algorithm, adding energy storage components, and optimizing the device configuration. These modifications enable the DVR to respond more quickly and effectively to various types of voltage disturbances, including complex and severe ones. Simulations and testing show that the modified DVR can better handle voltage fluctuations, thereby improving overall power stability and quality.

The use of the modified DVR shows significant improvements in power quality. Compared to a conventional DVR, the modifications allow the DVR to maintain voltage within tighter limits, reduce the frequency and duration of voltage disturbances, and provide better protection for sensitive equipment. Simulation results show improved operational efficiency and reduced maintenance costs due to equipment failures.

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