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PERFORMANCE ENHANCEMENT OF PMSG-BASED SMALL HYDRO POWER SYSTEMS USING BATTERY-SUPPORTED UPQC

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ABSTRACT

The growing penetration of renewable energy sources, power electronic interfaces, and nonlinear as well as unbalanced loads has significantly increased power quality (PQ) challenges in modern distribution systems. Addressing these PQ issues is essential to ensure reliable operation, improved efficiency, and reduced operational costs. This paper presents a unified power quality conditioner (UPQC) integrated with a standalone hydro-electric power generation system to simultaneously improve voltage and current quality. A permanent magnet synchronous generator (PMSG), driven by a hydro turbine, supplies power to sensitive local loads. A model predictive control (MPC) strategy is employed to generate optimal switching signals for the UPQC converters. The series compensator mitigates voltage disturbances and maintains load voltage at a constant rated magnitude with low harmonic distortion under varying operating conditions. Meanwhile, the shunt compensator ensures sinusoidal generator currents, supplies reactive power demand, and enforces unity power factor operation of the PMSG, thereby reducing system losses. In addition, a battery energy storage system supports stable operation during transient and load variations. The proposed system is validated through detailed MATLAB/Simulink simulations under multiple test conditions.

Keywords: PQ, UPQC, PMSG, MPC, Battery Energy Storage System

I INTRODUCTION

The growing penetration of renewable energy sources in standalone power systems has increased concerns related to voltage regulation and power quality, particularly in the presence of nonlinear and unbalanced loads. Small-scale hydroelectric generation has gained prominence due to its reliability and low environmental impact. However, the integration of power electronic interfaces often introduces harmonics, reactive power demand, and voltage distortions that degrade system performance.

Permanent magnet synchronous generators (PMSGs) are well suited for standalone hydroelectric applications because of their high efficiency, compact design, and absence of external excitation. Despite these advantages, PMSG-based isolated systems experience voltage variations and poor power quality under dynamic load conditions, which can adversely affect sensitive and critical loads requiring stable and distortion-free power supply.

To address these challenges, this paper presents a unified power quality conditioner (UPQC) controlled using a model predictive control (MPC) strategy and integrated with a PMSG-driven standalone hydroelectric system supported by battery energy storage. The proposed approach effectively mitigates voltage and current harmonics, maintains constant load voltage, improves power factor, and enhances overall system reliability under various operating conditions.

II LITERATURE SURVEY

In recent years, the increasing deployment of renewable energy–based standalone power systems has drawn significant research attention due to their suitability for remote and off-grid applications. Among various renewable sources, small-scale hydroelectric power generation has been widely explored because of its reliability, high efficiency, and minimal environmental impact. However, the integration of nonlinear loads and power electronic interfaces in standalone systems has introduced serious power quality issues such as voltage distortion, current harmonics, reactive power burden, and load unbalance, which negatively affect system stability and reliability.

Early research on standalone hydroelectric systems primarily focused on induction generator–based configurations due to their rugged structure and low cost. Nevertheless, induction generators require external reactive power support and suffer from poor voltage regulation under varying load conditions. To overcome these limitations, permanent magnet synchronous generators (PMSGs) have been increasingly adopted in recent studies. PMSG-based systems offer advantages such as self-excitation, high efficiency, compact design, and improved performance under variable-speed operation. Despite these benefits, PMSG-based standalone systems still face voltage fluctuation and power quality degradation when supplying nonlinear and sensitive loads.

To address power quality problems in standalone renewable energy systems, several compensation techniques have been proposed in the literature, including shunt active power filters, series compensators, and hybrid compensation schemes. Among these solutions, the Unified Power Quality Conditioner (UPQC) has emerged as an effective custom power device capable of simultaneously mitigating voltage- and current-related disturbances. UPQC integrates both series and shunt voltage source inverters, enabling compensation of voltage sags/swells, current harmonics, reactive power, and load unbalance in a single structure. Most of the reported UPQC-based systems employ conventional control strategies such as proportional–integral (PI), proportional–resonant (PR), and synchronous reference frame (SRF)–based controllers. Although these methods are widely used, their performance is highly dependent on accurate controller tuning and system parameters. Moreover, the effectiveness of these controllers degrades under dynamic operating conditions, frequency variations, and nonlinear load disturbances, making them less suitable for standalone renewable energy systems with fluctuating operating conditions.

Recently, advanced control techniques such as model predictive control (MPC) have been introduced for power electronic and power quality applications due to their fast dynamic response, ability to handle multivariable systems, and elimination of multiple controller tuning requirements. While MPC has shown promising results in grid-connected converters and active power filters, limited research has been reported on MPC-controlled UPQC integrated with standalone PMSG-based hydroelectric systems supported by battery energy storage. This research gap motivates the present work, which focuses on enhancing power quality, voltage regulation, and system reliability under various steady-state and dynamic operating conditions.

III EXISTING SYSTEM

The existing standalone hydroelectric power generation system primarily consists of a hydro turbine coupled to an electrical generator, commonly an induction generator or a permanent magnet synchronous generator (PMSG), supplying power directly to local loads. The hydro turbine converts the kinetic energy of flowing water into mechanical energy, which drives the generator shaft. The generator produces three-phase AC power, whose voltage magnitude and frequency vary depending on water flow conditions and connected load characteristics.

In this system, the generated power is directly fed to linear and nonlinear loads without advanced power quality conditioning. Nonlinear loads such as diode bridge rectifiers,

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converters, and electronic equipment draw harmonic-rich currents from the generator, resulting in distorted source currents and degraded voltage profiles at the load terminals. Due to the absence of effective compensation devices, voltage fluctuations, current harmonics, and load unbalance significantly affect system performance and reliability.

Reactive power support and voltage regulation in the existing system are typically achieved using passive components such as capacitor banks or shunt compensation techniques. Although these methods provide basic voltage support, they increase the reactive power demand from the generator, leading to poor power factor and higher losses. Furthermore, passive compensation is ineffective during dynamic operating conditions such as sudden load changes, voltage dips, or unbalanced loading scenarios.

The below fig (i) shows the block diagram of the proposed standalone hydro- electric power system integrated with UPQC for power quality improvement.

BLOCK DIAGRAM:

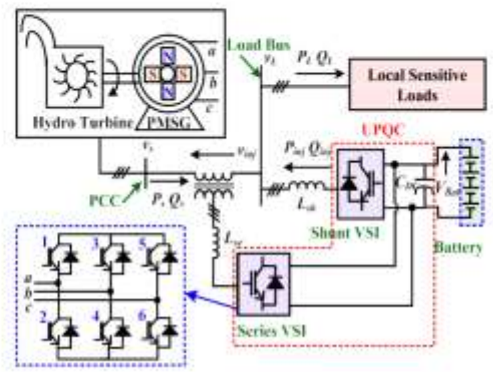

Fig:(i) Block Diagram of the Proposed Standalone Hydro-Based UPQC System

Conventional Control strategies such as proportional–integral(PI),proportional–resonant (PR), or synchronous reference frame–based controllers are often employed in existing systems for basic regulation purposes. These controllers require multiple control loops and accurate parameter tuning, making the system complex and less robust. Their performance degrades under frequency variations and nonlinear load disturbances, limiting their effectiveness in maintaining power quality. Overall, the existing system lacks coordinated voltage and current compensation, resulting in poor power quality, reduced efficiency, and unreliable operation when supplying sensitive and critical loads. These limitations highlight the need for an advanced power quality enhancement solution capable of simultaneously addressing voltage regulation, harmonic mitigation, reactive power compensation, and dynamic load variations.

IV PROPOSED SYSTEM:

The proposed system presents an enhanced PMSG based standalone hydro-electric power generation system integrated with a battery supported Unified Power Quality Conditioner (UPQC) to improve overall power quality and system reliability. The primary objective of this system is to ensure continuous power delivery while mitigating voltage and current related power quality disturbances under varying load conditions.

In this system, the hydro turbine converts the kinetic energy of flowing water into mechanical energy, which is utilized to drive a Permanent Magnet Synchronous Generator (PMSG). The electrical output generated by the PMSG is converted into DC power through an AC–DC converter and fed to a common DC link. A Battery Energy Storage System (BESS) is connected across the DC link to maintain voltage stability and provide energy support during sudden load variations or transient disturbances.

The DC link supplies power to a Unified Power Quality Conditioner (UPQC) comprising a series converter and a shunt converter. The series converter is responsible for compensating supply-side voltage disturbances such as sag, swell, and imbalance by injecting appropriate voltage components. The shunt converter is connected in parallel with the load and is employed to eliminate current harmonics, compensate reactive power, and maintain a near-unity power factor at the point of common coupling.

To achieve fast dynamic response and effective compensation, a predictive control strategy is implemented. This control approach predicts the future behavior of system variables and generates optimal switching signals for both converters, thereby improving transient performance and reducing steady-state errors. The integration of battery support with UPQC further enhances system reliability, making the proposed configuration suitable for supplying sensitive and nonlinear loads in standalone hydro-electric applications. The below fig (ii)shows the circuit-level implementation of the proposed UPQC-based power quality enhancement system.

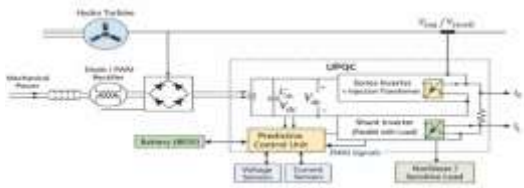

Fig:(ii). Circuit Configuration of the Proposed PMSG-Based Standalone System with UPQC

V MAT LAB/ SIMULATION RESULTS

PROPOSED MODLE:

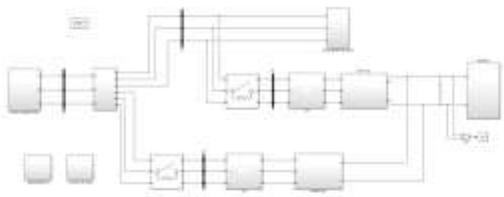

Fig: Proposed Model of the Standalone Hydro-Electric System with Reduced-Switch UPQC

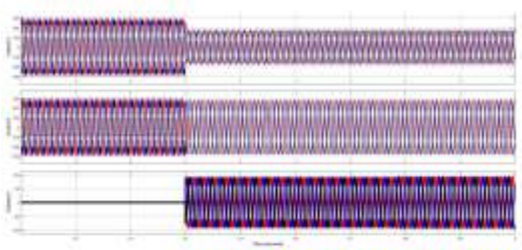

Fig: (a) This figure (a) illustrates how the predictive-controlled UPQC injects a compensating series voltage to correct source voltage disturbances and maintain a stable, sinusoidal load voltage

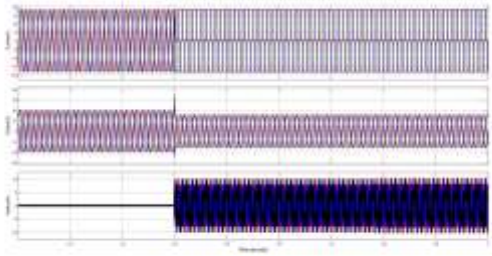

Fig:(b)This figure (b) shows the three-phase load current (IL abc) waveforms, demonstrating effective harmonic mitigation and balanced current operation after compensation by the proposed UPQC.

Dynamic performance:

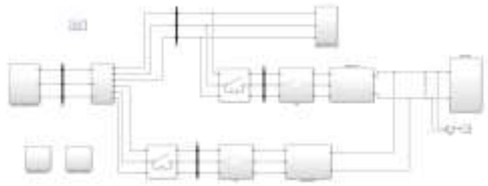

Fig: Dynamic Performance of the Proposed Reduced-Switch UPQC under Load Variation

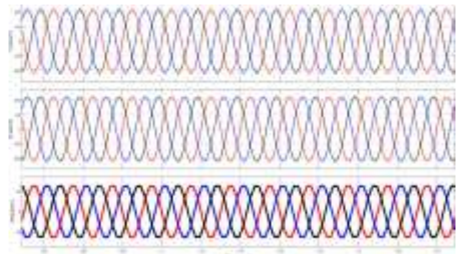

Fig:(a). Dynamic performance of During Load Unbalancing Condition. Vs,abc, Vl.abc, Vinj, abc.

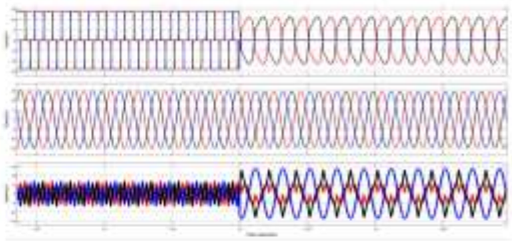

Fig:(b). Dynamic performance of During Load Unbalancing Condition. Is,abc, Il.abc, Iinj,abc.

DC-Link Voltage and Power Response of the Proposed System

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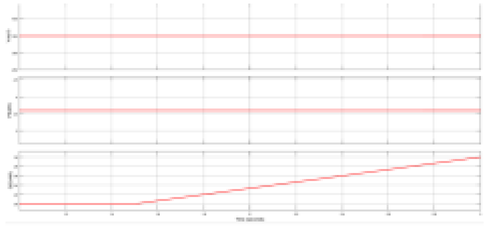

Fig:(C). Dynamic performance of During Load Unbalancing Condition. VDC, Ps, Qs

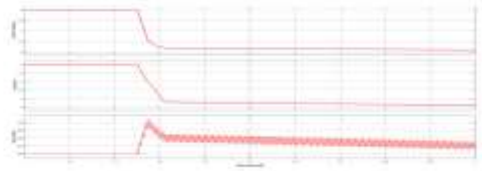

Fig:(d). Dynamic performance of During Load Unbalancing Condition. PBATT, PL&QL.

The performance of the proposed PMSG based hydro-electric power system integrated with a battery supported Unified Power Quality Conditioner (UPQC) using predictive control has been evaluated through detailed simulation studies under various operating conditions. The results clearly demonstrate the effectiveness of the proposed system in mitigating power quality issues caused by nonlinear and unbalanced loads. When the UPQC is not connected, the system experiences significant voltage distortions such as sag and swell at the load terminals, along with highly distorted source currents containing considerable harmonic components. After enabling the series and shunt converters of the UPQC, the voltage and current waveforms become nearly sinusoidal and balanced. The series converter effectively compensates voltage disturbances by injecting appropriate compensating voltages, thereby maintaining a constant and regulated load voltage even during sudden disturbances. Simultaneously, the shunt converter successfully eliminates current harmonics and provides reactive power compensation, resulting in improved power factor and reduced losses. The battery energy storage system connected to the DC link plays a crucial role in stabilizing the DC link voltage during load variations and transient conditions, ensuring uninterrupted power flow and enhanced system reliability. Furthermore, the implementation of predictive control enables fast dynamic response and accurate tracking of reference signals, which significantly improves transient performance compared to conventional control techniques. The total harmonic distortion (THD) of the source current is considerably reduced and maintained within acceptable limits, satisfying power quality standards. Overall, the obtained results confirm that the proposed system not only enhances voltage and current quality but also improves system stability, reliability, and efficiency, making it highly suitable for standalone hydro-electric power applications supplying sensitive and nonlinear loads.

VI CONCLUSION

The Solar-Powered Air Quality Monitoring and Control System offers a dependable, efficient, and long-lasting answer to contemporary environmental safety issues. The system guarantees continuous operation even in locations with inconsistent or non-existent grid power by combining renewable solar energy with embedded technologies and Internet of Things technology. Efficient power management and battery backup boost system stability during low sunlight situations. The system continuously monitors essential air quality factors such as hazardous gasses, particulate matter, temperature, and humidity. Real-time data processing by the microcontroller provides accurate evaluation of environmental conditions. This initiative actively reduces risks by automatically regulating exhaust fans or air purifiers, in contrast to traditional systems that merely offer passive monitoring. Local notifications through LCD displays and buzzers ensure rapid awareness for on-site users. IoT connectivity offers remote monitoring, data visualization, and long-term analysis through cloud platforms. Both users and supervisors benefit from increased accessibility and situational awareness. The architecture's scalability and modularity make it simple to add more sensors. In both indoor and outdoor settings, the system operates effectively. The usage of renewable energy lowers operating costs. All

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things considered, the project effectively blends automation, intelligence, and sustainability. For proactive air quality monitoring and environmental protection, it is therefore a workable and future-ready option.

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