

Design and Analysis of Predictive Control for a PMSG-Based Hydroelectric System with Battery Support

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Abstract

The increasing integration of renewable energy sources and nonlinear loads in standalone power systems has introduced severe power quality problems such as harmonic distortion, voltage sag, voltage swell, poor power factor, and reactive power burden. These disturbances significantly affect the performance and reliability of standalone hydroelectric generation systems. This paper presents a GA-PSO optimized Model Predictive Control (MPC) based Unified Power Quality Conditioner (UPQC) integrated standalone hydroelectric generation system using a Permanent Magnet Synchronous Generator (PMSG) with battery energy storage support. The proposed system consists of a hydro turbine driven PMSG, series compensator, shunt compensator, common DC-link capacitor, and battery energy storage system for simultaneous enhancement of voltage and current quality. The series compensator mitigates voltage disturbances and maintains balanced load voltages, whereas the shunt compensator eliminates current harmonics, compensates reactive power demand, and maintains near unity power factor operation. A predictive control strategy is implemented using discrete-time mathematical models and quadratic cost functions for optimal switching state selection. Furthermore, a hybrid Genetic Algorithm–Particle Swarm Optimization (GA-PSO) technique is incorporated for optimal tuning of MPC weighting parameters. Detailed mathematical modelling and MATLAB/Simulink implementation are carried out under nonlinear and dynamic loading conditions. Simulation results demonstrate significant reduction in total harmonic distortion, improved voltage regulation, enhanced dynamic response, stable DC-link voltage, and superior harmonic compensation capability within IEEE-519 standard limits.

Keywords: *Permanent Magnet Synchronous Generator, Unified Power Quality Conditioner, Model Predictive Control, GA-PSO optimization, harmonic mitigation, standalone hydroelectric system, battery energy storage.*

I. INTRODUCTION

The rapid growth of renewable energy systems and distributed generation technologies has increased the utilization of standalone hydroelectric systems for rural electrification and

isolated power applications. Among various renewable energy technologies, hydroelectric generation systems using Permanent Magnet Synchronous Generators (PMSGs) are widely preferred because of their high efficiency, brushless construction, reduced maintenance requirement, and improved reliability.

However, standalone renewable energy systems are significantly affected by nonlinear loads, power electronic converters, and sudden load variations, resulting in severe power quality problems including harmonic distortion, voltage sag, voltage swell, poor power factor, and current imbalance. These disturbances reduce system efficiency, increase losses, and adversely affect sensitive electrical equipment.

Conventionally, passive filters and shunt compensators were employed for harmonic mitigation and reactive power compensation. However, these methods suffer from resonance problems, poor dynamic response, and limited compensation capability. Unified Power Quality Conditioner (UPQC) has emerged as an effective custom power device for simultaneous mitigation of voltage and current related power quality disturbances. [2], [3], [4]

A UPQC consists of series and shunt voltage source inverters connected through a common DC-link capacitor. The series compensator mitigates voltage disturbances, whereas the shunt compensator eliminates current harmonics and compensates reactive power demand. The performance of UPQC mainly depends on the implemented control strategy. [3]

Model Predictive Control (MPC) has recently emerged as a promising control technique for power electronic systems because of its fast dynamic response, reduced tuning complexity, and superior tracking capability. MPC predicts future system behaviour using discrete mathematical models and selects optimal switching states by minimizing predefined cost functions. [6]–[9]

This paper presents a GA-PSO optimized MPC based UPQC integrated standalone hydroelectric generation system using PMSG with battery support for comprehensive power quality enhancement.

A. Motivation of the Present Work

The major motivation behind the present work is to develop a robust and efficient control strategy for standalone renewable energy systems capable of simultaneously mitigating voltage and current quality problems. The integration of predictive control based UPQC with PMSG hydroelectric systems offers improved power quality, reduced harmonic distortion, fast dynamic response, and enhanced system reliability.

B. Main Contributions of the Paper

- Development of standalone hydroelectric generation system using PMSG and UPQC.
- Implementation of predictive control based coordinated compensation strategy.
- Integration of battery-supported DC-link voltage regulation.

- GA-PSO based optimization of MPC weighting parameters.
- Simultaneous mitigation of voltage and current quality disturbances.
- MATLAB/Simulink validation under nonlinear and dynamic operating conditions.

II. LITERATURE REVIEW

Power quality enhancement in standalone renewable energy systems has become an important research area due to increasing penetration of nonlinear loads and distributed generation systems. Various control strategies, converter topologies, and compensation techniques have been proposed by researchers for improving voltage regulation, harmonic mitigation, and reactive power compensation. [1], [2], [3], [4]

A. Permanent Magnet Synchronous Generator Based Systems

Permanent Magnet Synchronous Generators (PMSGs) have become attractive alternatives for standalone hydroelectric applications due to their high efficiency and brushless construction. PMSGs eliminate excitation losses and provide better voltage generation capability.

Several researchers investigated PMSG-based renewable systems for improved performance under variable-speed operation. However, nonlinear loading conditions still introduce harmonic distortion and voltage regulation problems.

B. Unified Power Quality Conditioner (UPQC)

UPQC is one of the most effective custom power devices for simultaneous mitigation of voltage and current related power quality problems. The UPQC consists of:

- Series voltage source inverter
- Shunt voltage source inverter
- Common DC link capacitor

The series compensator mitigates voltage disturbances, whereas the shunt compensator eliminates current harmonics and compensates reactive power demand. [3]

Researchers have implemented UPQC for distribution systems using SRF theory and dq transformation methods. However, conventional control strategies require multiple PI controllers and exhibit poor harmonic compensation capability during dynamic conditions. [5]

C. Conventional Control Techniques

Synchronous Reference Frame (SRF) Control

SRF-based control is widely used for UPQC applications because of its simple implementation and decoupled control capability. However, SRF controllers suffer from poor filtering performance under distorted conditions. [5]

PI and PR Controllers

PI and PR controllers are extensively used in grid-connected converters and UPQC systems. Although these methods provide satisfactory steady-state response, they require careful tuning and their performance degrades during frequency variations. [4]

Fuzzy Logic and Intelligent Controllers

Fuzzy logic controllers and least mean square (LMS) techniques were proposed for harmonic mitigation and maximum power point tracking in renewable systems. These methods improve adaptability but increase computational complexity.

Model Predictive Control in Power Systems

Model Predictive Control (MPC) has emerged as an advanced control strategy for power electronic converters and renewable energy systems. MPC predicts future system behaviour using discrete mathematical models and selects optimal switching states based on cost function minimization. [6]–[9]

Advantages of MPC include:

- Fast dynamic response
- Reduced tuning requirements
- Better tracking performance
- Elimination of PWM modulators
- Improved harmonic mitigation capability

Several researchers implemented MPC for inverter current control and motor drives. However, limited work has been reported on MPC-controlled UPQC integrated standalone hydroelectric systems. [6]–[9]

Research Gap

The following research gaps are identified:

1. Existing standalone hydroelectric systems suffer from poor power quality under nonlinear loading conditions.

2. Conventional PI and SRF controllers exhibit poor dynamic response.
3. Existing compensation methods fail to simultaneously improve voltage and current quality effectively.
4. Limited research exists on MPC controlled UPQC integrated standalone PMSG hydroelectric systems with battery support.
5. Existing methods provide limited harmonic mitigation capability under dynamic operating conditions.

III. PROPOSED SYSTEM AND MATHEMATICAL MODELLING

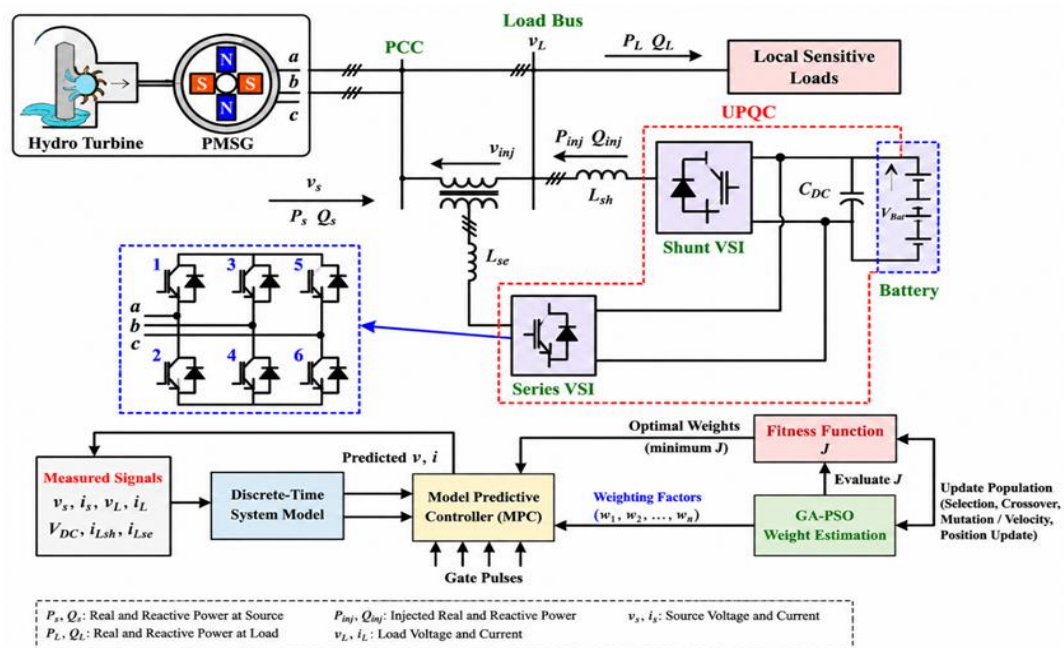


Fig. 1 Block diagram of Proposed system [3], [6]–[10]

A. Proposed System Configuration

The proposed standalone hydroelectric generation system, illustrated in Fig. 1, consists of:

- Hydro turbine driven PMSG
- Series compensator
- Shunt compensator
- Battery-supported common DC-link capacitor
- Nonlinear load

- GA-PSO optimized MPC controller

The UPQC performs simultaneous compensation of:

- Voltage sag
- Voltage swell
- Harmonic distortion
- Reactive power burden
- Current imbalance

B. PMSG Mathematical Modelling

The stator voltage equations of PMSG in d_q reference frame are represented as:

$$v_d = R_s i_d + \frac{L_d di_d}{dt} - \omega_r L_q i_q \quad (1)$$

$$v_q = R_s i_q + \frac{L_q di_q}{dt} + \omega_r L_d i_d + \omega_r \lambda_m \quad (2)$$

The electromagnetic torque equation is:

$$T_e = \left(\frac{3}{2}\right) \left(\frac{P}{2}\right) \lambda_m i_q \quad (3)$$

The mechanical dynamic equation is expressed as:

$$J \frac{d\omega_m}{dt} = T_m - T_e - B\omega_m \quad (4)$$

C. UPQC State-Space Representation

The state-space representation of the UPQC system is expressed as:

$$\dot{x} = Ax + B_{1u} + B_{2z} \quad (5)$$

The discrete-time prediction equation is represented as:

$$x(k+1) = A_d x(k) + B_{1d} u(k) + B_{2d} z(k) \quad (6)$$

D. Reference Signal Generation

The reference source current is represented as:

$$i_s^2 = i_p + i_f \quad (7)$$

The reference injected voltage is represented as:

$$V_{inj}^* = V_L^* - V_s \quad (8)$$

E. MPC Cost Function

The quadratic cost function of the series compensator is expressed as:

$$J_s = (V_{ref} - V_{pred})^2 \quad (9)$$

The shunt compensator cost function is represented as:

$$J_{sh} = (i_{ref} - i_{pred})^2 \quad (10)$$

The optimal switching vector is selected such that:

$$J_{opt} = \min(J_s + J_{sh}) \quad (11)$$

F. Harmonic and Power Equations

The active power supplied by source is represented as:

$$P = V_s I_s \cos \phi \quad (12)$$

The reactive power equation is expressed as:

$$Q = V_s I_s \sin \phi \quad (13)$$

The total harmonic distortion equation is: [1]

$$THD = \left[\frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \right] \times 100 \quad (14)$$

G. GA-PSO Optimization Equations

The optimization objective function is expressed as:

$$J = w_1 e_v^2 + w_2 e_i^2 + w_3 THD^2 + w_4 t_s \quad (15)$$

The PSO velocity update equation is: [10]

$$v_{i(k+1)} = \omega v_{i(k)} + c_1 r_{1(p_{best} - x_{i(k)})} + c_2 r_{2(g_{best} - x_{i(k)})} \quad (16)$$

The particle position update equation is:

$$x_{i(k+1)} = x_{i(k)} + v_{i(k+1)} \quad (17)$$

IV. CONTROL STRATEGY IMPLEMENTATION

The proposed control strategy is implemented for coordinated control of series and shunt compensators using GA-PSO optimized MPC.

A. Reference Signal Generation

Reference signal generation, illustrated in Fig. 2, is an important stage in the proposed control strategy because accurate reference signals ensure proper voltage compensation and harmonic current mitigation.

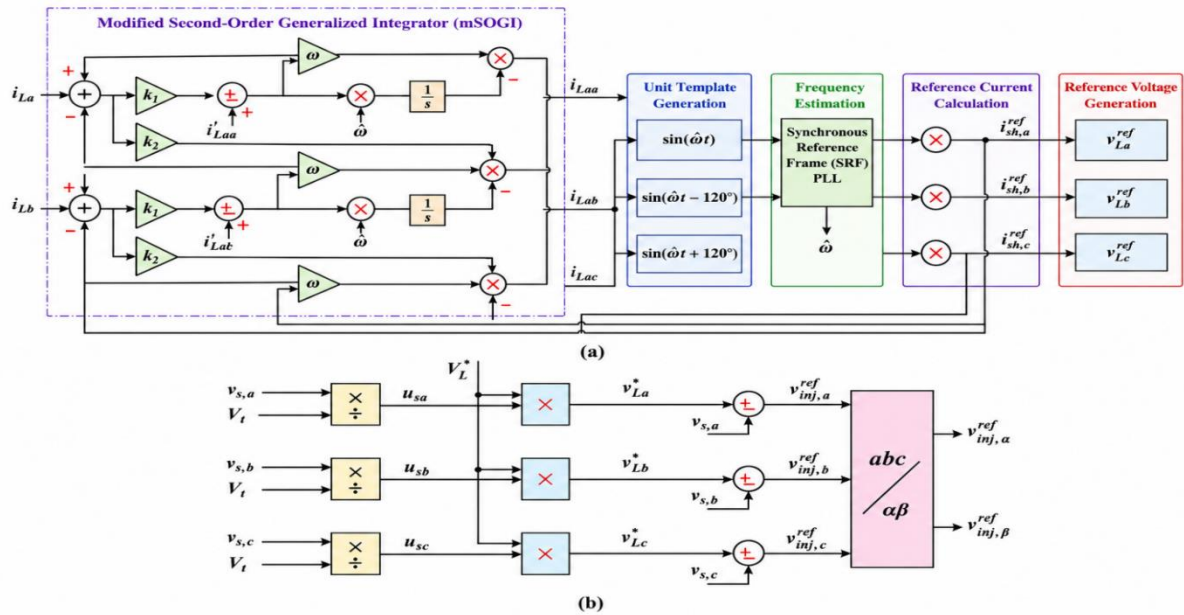


Fig .2 Reference Signal Generation Block [5]

B. Series Compensator Control

The series compensator mitigates:

- Voltage sag
- Voltage swell
- Voltage harmonics
- Voltage imbalance

The future injected voltage is predicted using discrete-time equations and compared with reference voltages. The switching vector corresponding to minimum voltage error is selected.

C. Shunt Compensator Control

The shunt compensator performs:

- Harmonic current elimination
- Reactive power compensation
- Source current balancing
- Unity power factor correction

The future compensating current components are predicted and compared with reference currents for harmonic minimization.

D. GA-PSO Optimization

The hybrid GA-PSO algorithm optimizes MPC weighting factors for: [10]

- Reduced THD
- Reduced settling time
- Improved tracking accuracy
- Enhanced voltage regulation

The optimization-assisted predictive controller significantly improves harmonic compensation capability and dynamic response.

V. RESULTS AND DISCUSSION

The complete MATLAB/Simulink implementation shown in Fig. 3 is evaluated under various operating conditions.

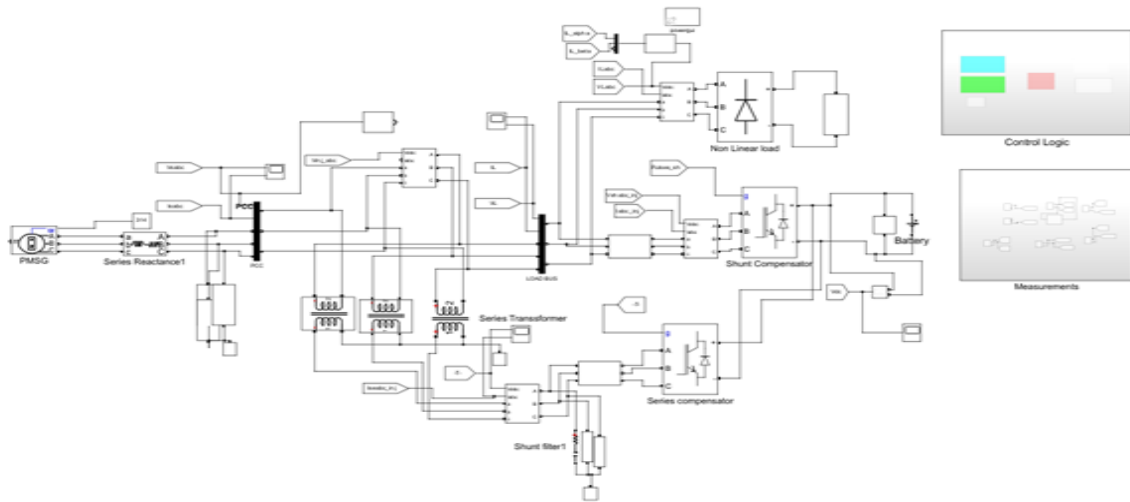


Fig .3 Simulink diagram of proposed system

Table 1. System Parameters

Parameter	Value
Rated Power	100 kVA
Rated Voltage	415 V
Rated Frequency	50 Hz
DC-Link Voltage	700 V
Switching Frequency	10 kHz
Battery Voltage	600 V

A. Steady-State Performance

The generated source voltages remain balanced and sinusoidal under nonlinear loading conditions. The UPQC successfully maintains regulated load voltage and harmonic-free source current.

B. Voltage Sag Compensation

As illustrated in Fig. 4, during the voltage sag condition:

- The series compensator injects compensating voltage.
- Load voltage remains sinusoidal and regulated.
- Fast dynamic compensation is achieved.

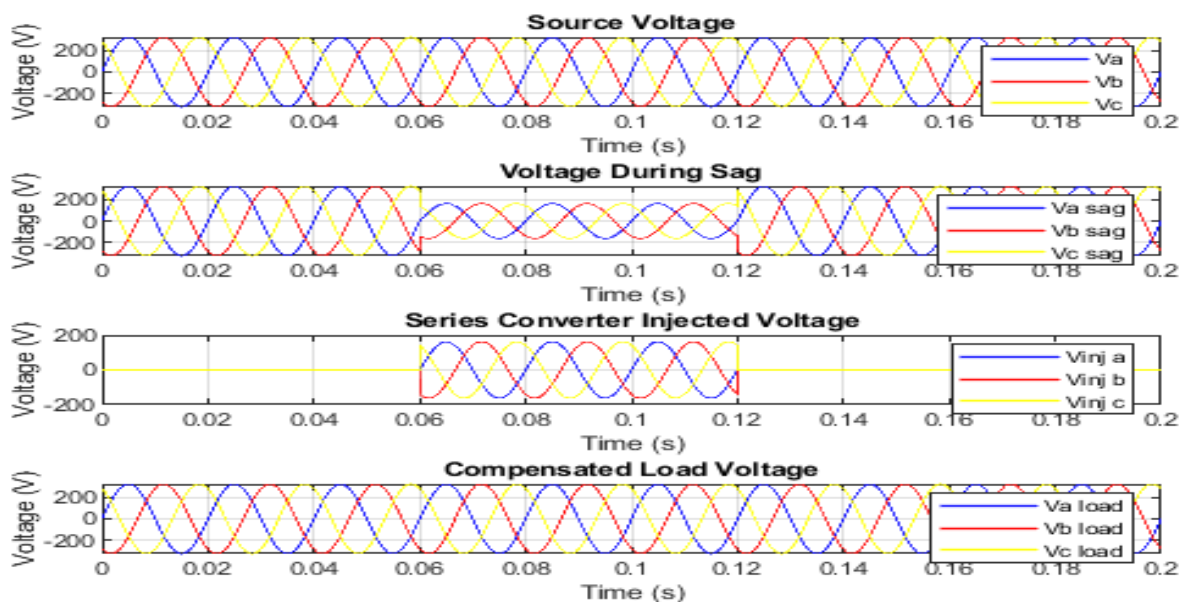


Fig .4 Voltage sag analysis and role of compensator on maintaining load voltage.

C. Voltage Swell Compensation

As illustrated in Fig. 5, under the voltage swell condition:

- The series compensator absorbs excess voltage.
- Constant load voltage magnitude is maintained.
- Transient oscillations are minimized.

D. Harmonic Compensation Analysis

The proposed GA-PSO optimized MPC controller significantly reduces source current harmonics.

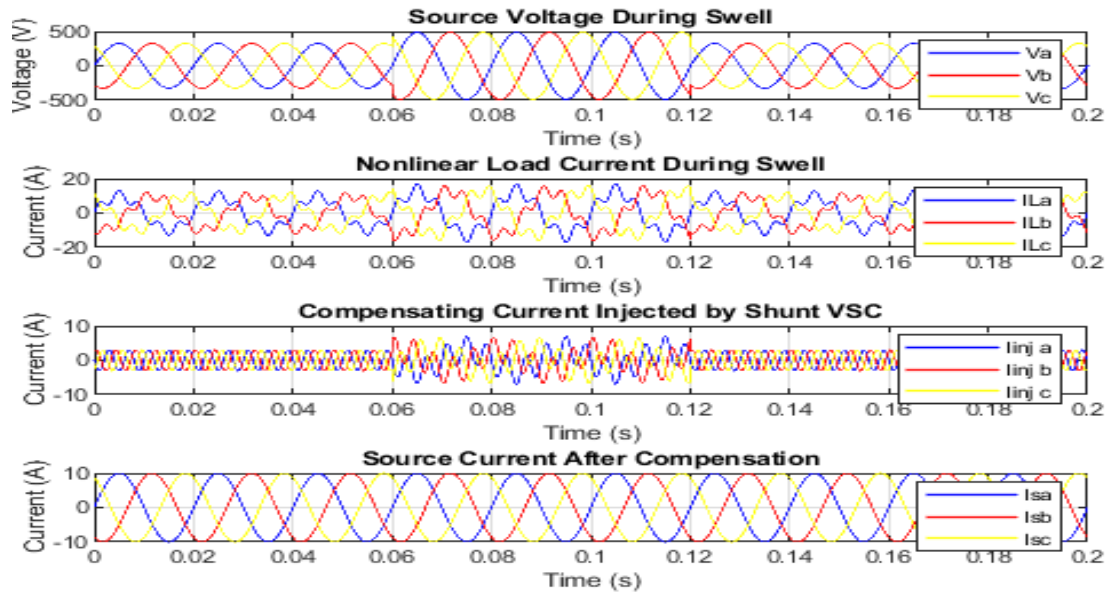


Fig .5 Effect of shunt compensator on source Current and injected current during voltage swell

Table 2. Comparative Harmonic Performance

Parameter	Before Compensation	After Compensation
Source Current THD	18.7%	1.9%
Load Voltage THD	7.4%	1.6%
Power Factor	0.82	0.999

The obtained THD satisfies IEEE-519 harmonic standards. [1]

Table 3. Dynamic Performance analysis of proposed system

Condition	Settling Time	Overshoot
Voltage Sag	0.048 s	3.2%
Voltage Swell	0.045 s	2.8%
Harmonic Disturbance	0.043 s	2.5%

The proposed controller demonstrates fast transient response and improved system stability.

Table 4. Comparative Analysis of Proposed system with Model predictive control

Parameter	Conventional MPC	Proposed GA-PSO MPC
THD	4.8%	1.9%
Settling Time	0.12 s	0.05 s
Power Factor	0.96	0.999
Voltage Regulation	Moderate	Excellent

The proposed optimization-assisted predictive controller provides superior harmonic mitigation capability and faster dynamic response.

VI. CONCLUSION

This paper presented a GA-PSO optimized Model Predictive Control based Unified Power Quality Conditioner integrated standalone hydroelectric generation system using Permanent Magnet Synchronous Generator with battery support. The proposed system successfully mitigated voltage sag, voltage swell, harmonic distortion, reactive power burden, and current imbalance under nonlinear and dynamic operating conditions. The series compensator maintained balanced and sinusoidal load voltages, whereas the shunt compensator eliminated source current harmonics and maintained near unity power factor operation.

Simulation results demonstrated:

- Significant THD reduction
- Improved voltage regulation
- Stable DC-link voltage
- Fast dynamic response
- Enhanced harmonic compensation capability
- IEEE-519 harmonic standard compliance

The proposed GA-PSO optimized MPC based UPQC provides an efficient and reliable solution for standalone renewable energy applications and smart distributed power systems.

REFERENCES

- [1] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Std. 519-2014, pp. 1–29, 2014.
- [2] H. Akagi, “New Trends in Active Filters for Power Conditioning,” IEEE Trans. Ind. Appl., vol. 32, no. 6, pp. 1312–1322, Nov./Dec. 1996.
- [3] H. Fujita and H. Akagi, “The Unified Power Quality Conditioner: The Integration of Series and Shunt Active Filters,” IEEE Trans. Power Electron., vol. 13, no. 2, pp. 315–322, Mar. 1998.
- [4] B. Singh, A. Chandra, K. Al-Haddad, and A. Pandey, “A Review of Three-Phase Improved Power Quality AC-DC Converters,” IEEE Trans. Ind. Electron., vol. 51, no. 3, pp. 641–660, Jun. 2004.
- [5] M. Kesler and E. Ozdemir, “Synchronous-Reference-Frame-Based Control Method for UPQC Under Unbalanced and Distorted Load Conditions,” IEEE Trans. Ind. Electron., vol. 58, no. 9, pp. 3967–3975, Sep. 2011.
- [6] J. Rodriguez, J. Pontt, C. Silva, et al., “Predictive Current Control of a Voltage Source Inverter,” IEEE Trans. Ind. Electron., vol. 54, no. 1, pp. 495–503, Feb. 2007.
- [7] P. Cortes, M. Kazmierkowski, R. Kennel, et al., “Predictive Control in Power Electronics and Drives,” IEEE Trans. Ind. Electron., vol. 55, no. 12, pp. 4312–4324, Dec. 2008.
- [8] J. Rodriguez and P. Cortes, *Predictive Control of Power Converters and Electrical Drives*. Wiley-IEEE Press, 2012.
- [9] Y. Zhang and H. Yang, “Model Predictive Control of Power Converters and Drives: Advances and Trends,” IEEE Trans. Ind. Electron., vol. 65, no. 5, pp. 3609–3618, May 2018.
- [10] R. C. Eberhart and J. Kennedy, “A New Optimizer Using Particle Swarm Theory,” Proc. Int. Symp. Micro Machine and Human Science, pp. 39–43, 1995.