

Enhanced UPQC Control System for Power Quality Improvement in Wave Energy-Driven PMSG Systems

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Abstract -This article explains the use of a unified power quality conditioner (UPQC) to improve power quality (PQ) in a wave energy driven permanent magnet synchronous generator (PMSG) system with unbalanced and highly inductive nonlinear loads. Our suggested control method improves voltage quality, balances reactive power, and lowers harmonics. The UPQC uses a parallel converter to provide harmonic rejection, reactive power compensation, enhanced voltage quality, and stable voltage amplitudes amid supply voltage issues. Unlike previous approaches, we propose a frequency-fixed second-order generalised integrator (FFSOGI) quasi-type-1 PLL for effective source voltage defect detection and load harmonic extraction. Furthermore, a strong nonlinear proportional integral (N-PI) controller with a feed forward term quickly adjusts the DC-link voltage and minimises oscillations. Our method guarantees that the harmonics of the source current and load voltage satisfy IEEE standards. We demonstrate the benefits of our proposed method over existing methods using thorough PSCAD/EMTDC results and experimental torque and power data from a wave energy converter at the Australian Maritime College model test pool.

Key Words: Wave energy converter, UPQC, nonlinear loads.

INTRODUCTION

Renewable energy technology has recently advanced, creating opportunities to decarbonise power generation in outlying coastal towns. In these regions, wave energy has the potential to generate sustainable electricity with minimal impact on the environment. A large number of effective wave energy converters (WECs) are now operational across the globe [1]. The versatility of WECs has been shown in previous studies conducted at the kilowatt [2,3], and megawatt-scale [5] to meet a range of power needs. For very tiny island populations, the optimal power generation system is an autonomous one that uses wave energy to power a three-phase PMSG. Because of its inherent advantages, like self-excitation and simple voltage build-up, it is the superior choice. Power factor operation (UPF) must be maintained in a variety of load conditions, such as nonlinear, imbalanced, and highly inductive loads, and this can only be achieved with precise management. Nevertheless, the ability of PMSGs to generate voltage may diminish with age, and defects can lead to variations in output. The voltage-sensitive load will thus have

reduced impact from variations in the supply voltage. This is remedied by implementing UPQC [6] integration, which ensures a steady voltage, boosts power factor, reduces reactive power, and lessens harmonic distortion. You can use UPQC to solve voltage-related and current-related PQ problems simultaneously or independently. It makes the system more efficient and reliable.

A novel approach that employs series and parallel voltage source converters (VSCs) with common DC-coupling, the UPQC, is introduced in this work and successfully resolves a number of power quality challenges. The authors are unaware of any previous studies that have investigated the possibility of UPQC integration with WECs. Although both UPFC and UPQC are AC transmission system devices that can be adjusted to control the power system, UPQC is more commonly used to reduce power quality problems in distribution power systems, while UPFC is more commonly used to optimise the transmission system, power flow, and power factor correction.

The latter is the case that this study is focusing on. Several control strategies have been proposed recently due to the importance of an effective control approach for UPQC in improving power quality. For series converters, the authors of [7] used ANF, whereas for parallel converters, they used a logarithmic absolute filter. The research did not, however, incorporate data from systematic gain tweaking of the selected filters. The ANF does not account for gain normalisation, which might affect convergence when dealing with large magnitudes of voltage sag or swell. Isolated power systems are prone to grid-frequency variations, which can affect a quarter-delay-based QSG method that was discussed in [8]. In [9], a new approach was used to raise the computational complexity by utilising SOGI and several complex coefficient filters. The same study also proposed an FLPID controller to regulate the voltage on the DC-link. Sometimes adjusting the controller is a real pain, and adding derivative words might make it much more noise-sensitive.

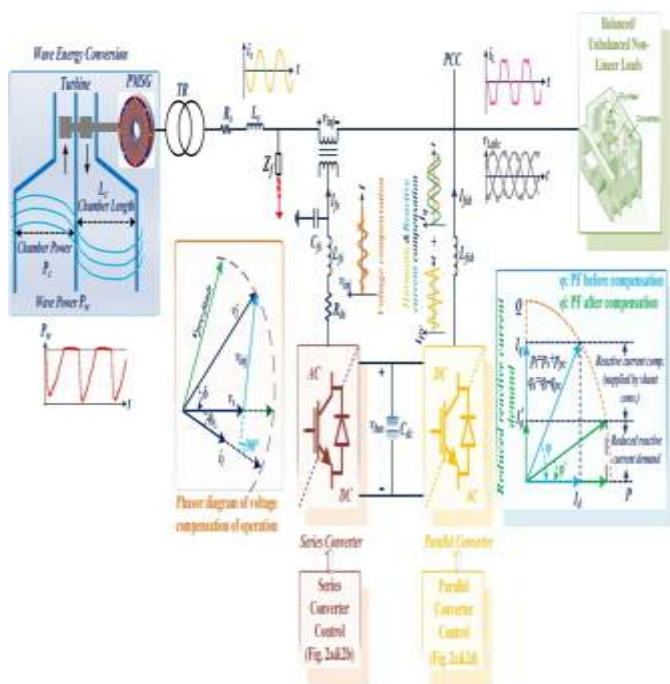
A high level of computational complexity is produced by the use of SOGI for UPQC control with a frequency-adaptive CF in [10]. While this choice reduces the switching frequency of the control system and makes filter design more challenging, [11] uses a GDSC filter to avoid fractional delays. The use of an LMS4 filter in [12] is not without its limitations; for example, the response speeds could be affected by sudden changes in the source voltage's amplitude, as there is no amplitude

normalisation. To make it more resilient, [13] employs sliding mode control with a disturbance observer. However, the widespread THD and limited overall control performance caused by the DC-link's conventional PI controller are major drawbacks. No tuning mechanism is provided, even though an adaptive vectorial filter is used as the basis for UPQC control in [14]. The lack of tuning gain in the employed FLL has resulted in the loss of design freedom. However, the variable leaky least-mean-square (LMS) method described in [15] improves upon the performance of traditional LMS filters by using an adaptable leakage factor and step size. The method's real-time applicability for inexpensive embedded systems is constrained, nevertheless, by its higher computational complexity.

2. UPQC IN WAVE ENERGY DRIVEN PMSG SYSTEM

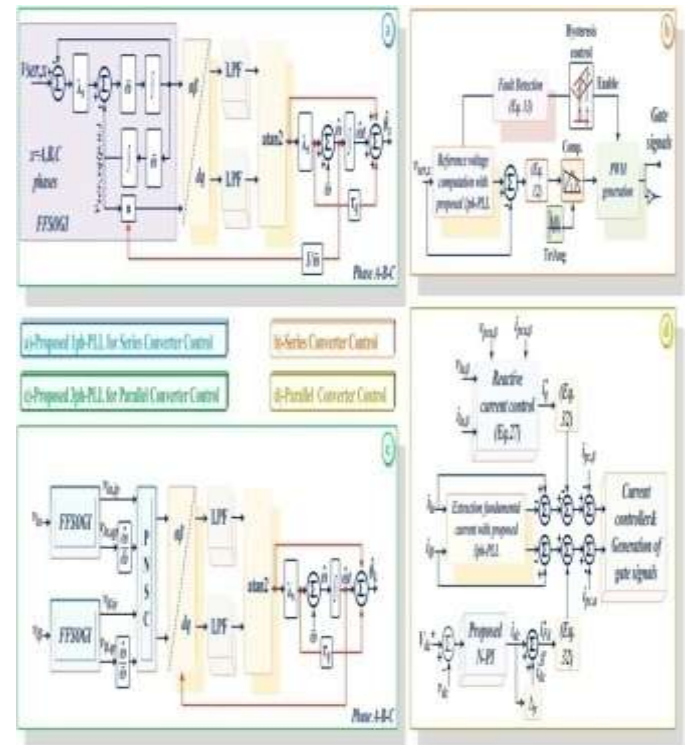
The UPQC is situated between the wave energy-driven PMSG and NLLs in the WEC-driven system design seen in Fig. 1. A substation with a transformer (TR) that transports all of the electricity to the coast is attached to the WECs. An oscillating water column-type WEC is connected to a single stage unidirectional air turbine system as the energy source.

Using any torque produced during the pressure dips as mechanical input to the generator; this turbine produces energy during the air intake phase. It is more effective than the bi-directional form, according to preliminary tests and current research. Crucially, in theory, this WEC does not have to run at a variable speed. Torque and power measurements from experiments conducted in the model test tank at the Australian Maritime College (AMC) are also used to study the system [5].



1. Configuration of the proposed OWC wave energy converter driven PMSG system with

Fig.2.Theproposedcontrolschemeincluding(a)proposed1phase PLL, (b)proposed control for the series converter control, (c)proposed 3-phase PLL, and(d)proposed control forth (e) parallel converter control



3.Results and Discussions

The proposed UPQC control scheme for a wave energy-driven PMSG system was implemented in PSCAD/EMTDC. It was validated under various challenging conditions, including nonlinear, highly inductive, unbalanced loads, and voltage faults. Experimentally obtained WEC torque and power data from the AMC's test pool [5] has been utilized to drive the PMSG for realistic validation, and the system and control parameters are listed in Table I.

A. Performance Analysis under Various Operating Conditions

This subsection presents results for the proposed UPQC-based control scheme in a wave energy-driven PMSG system, both with and without UPQC. It includes scenarios with sudden additions of nonlinear, highly inductive, unbalanced loads, as well as single and double line-to-ground (SLG) and (DLG) faults on the source side. The case study in Fig. 5 compares control performance of the system connected to a NLL. At 0.15 s, an additional highly inductive NLL is added to the point of common coupling (PCC). The parallel converter compensates for load current harmonics and supplies total reactive power without drawing from the PMSG-based WEC. Results demonstrate effective suppression of load voltage and source current harmonics caused by the NLL, regulation of the DC-bus voltage, and unity power factor (UPF) assurance. The proposed approach

reduces reactive power demand on the parallel converter. Traditional control lacks reactive power control, whereas the proposed control injects 4.1 kVar reactive powers for up to 0.15 s and then 8.8 kVar to enhance power factor and transient stability, especially under inductive load conditions.

Source current (i_{sa}) and load voltage (v_{La}) quality are improved with a THD of 2.01% and 0.7–1.1%, respectively, compared to conventional control with THD values of 13.4% and 7.1%. The results in Fig. 6 demonstrate substantial improvements in dynamic response and voltage-current harmonic reduction compared to conventional control. A 35% voltage sag SLG fault at 0.1 s and the addition of an NLL at 0.15 s were used for performance analysis. The proposed N-PI control significantly reduces settling times, fluctuations, and overshoots in DC-bus voltage dynamics. The contribution of FF current (i_{dc}^{ff}) accelerates system dynamics and helps reduce overshoot and settling time. Large oscillations in DC-bus voltage and unbalanced harmonics

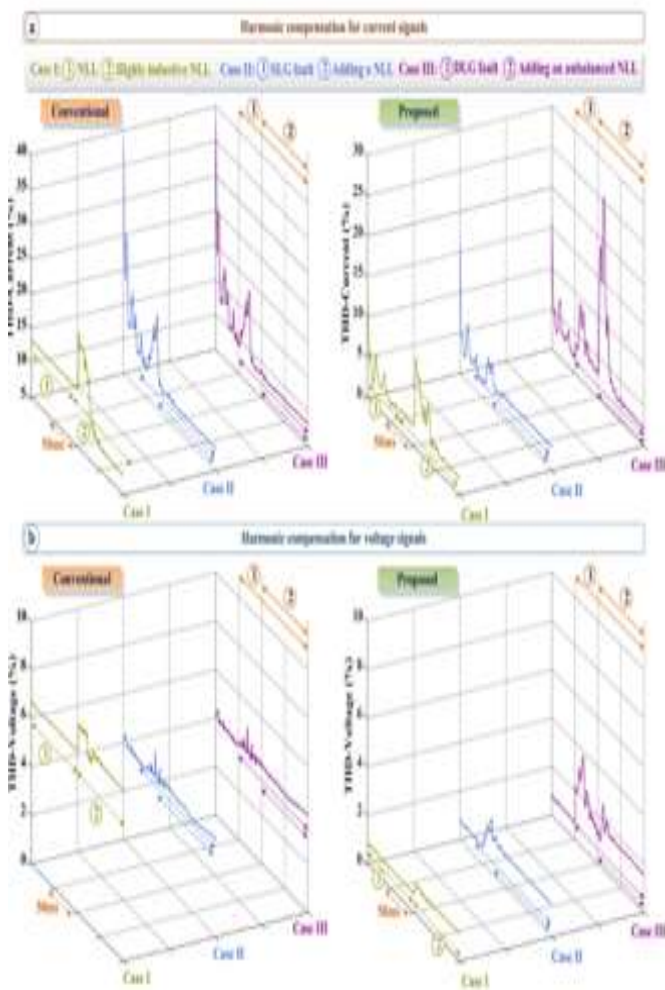


TABLE I
SYSTEM AND CONTROL PARAMETERS

System	Description	Specifications
PMSG	AC voltage (L-L)	380 V
	Frequency	50 Hz
	Power	50 kW
	Res. and Ind.	0.005 Ω , 0.1 mH
Series Converter	Injection transformer	4 kVA, 1 : 1 (110 V : 110 V)
	Damping resistor	0.7 Ω
	Filter cap. & ind.	200 μ F, 1 mH
Parallel Converter	Filter inductor	5 mH
	Harmonic current	20 – 30 A
	Reactive power	10 kVar $\pm$ 2 kVar
NLLs	Rectifier	15 + j3.15 Ω
	Highly inductive NLL	15 + j95 Ω
	UNLL	a: 40 – j80 Ω , b: 60 – j64 Ω , c: 30 – j106 Ω
DC-bus	Capacitor (Voltage)	2200 μ F(800 V)
	Switching freq.	10 kHz
FFSOGI	$\lambda_s, \tau_m, \lambda_l$	$\sqrt{2}, 5 \times 10^{-3}, 50$
N-PI	$\mu, \epsilon, \lambda_{k_p}, \lambda_{k_i}$	$5 \times 10^{-5}, 15, 50, 10^{-5}$

The proposed control scheme minimized DC-bus voltage deviation and exhibited negligible steady-state error ($\Delta v = 0.2$ V) during unbalanced NLL connection and supply voltage fault conditions. Source currents with the proposed control were nearly sinusoidal, balanced, and had a THD of 1.8%, while the power factor was nearly unity. In contrast, conventional control resulted in source currents with higher harmonics, unbalances, and a poor power factor. These results highlight the effectiveness and reliability of the proposed control, and a detailed comparison of source current and load voltage harmonics is provided in Section III-B. B. Comparative Analysis With the Existing Literature

Fig. 8 presents a detailed comparison of A-phase THDs (%) for load voltage and source current under various operating techniques. On the right side of Fig. 8, the proposed control maintains THDs of load voltage and source current below IEEE Std. 519 [16] acceptable limits. Specifically, the THD of source current (around 1.5–2.0%) is significantly lower than the 5% IEEE standard, and the THD of load voltage is below 1.0%, in compliance with IEEE standards. The proposed method employs a harmonically robust PLL along with an adjustable gain controller, which applies substantial control action for large errors to rapidly reach the reference voltage and smaller action for smaller errors, preventing ripple amplification. These factors

distinguish the proposed approach from the conventional counterpart [14]. a comparison between the proposed control scheme and recent literature is provided. The UPQC-interfaced wave energy-driven PMSG system with the proposed control outperforms existing methods in terms of reduced THD in source current and load voltage, power factor improvement, accurate fault level tracking, dynamic DC-bus voltage control, and reactive power compensation. The proposed method demonstrates superiority over existing control methods.

4.Simulation Result Analysis

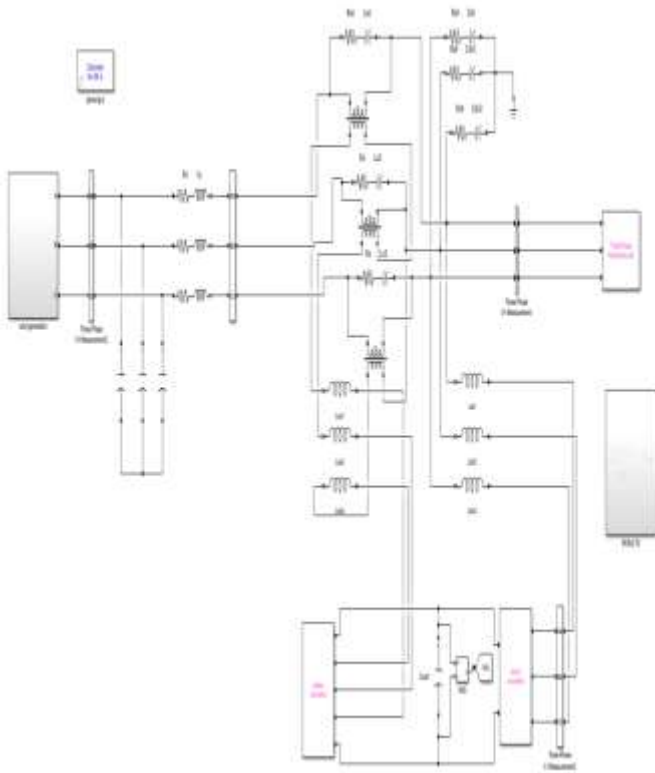


Fig.3. Simulation model

This is a MATLAB/Simulink Sim scape Power Systems model of a grid-connected power system containing a Unified Power Quality Conditioner (UPQC) connected to a wind generation source and a non-linear load.

The UPQC is a advanced power electronics device used to mitigate both voltage and current power quality disturbances simultaneously.

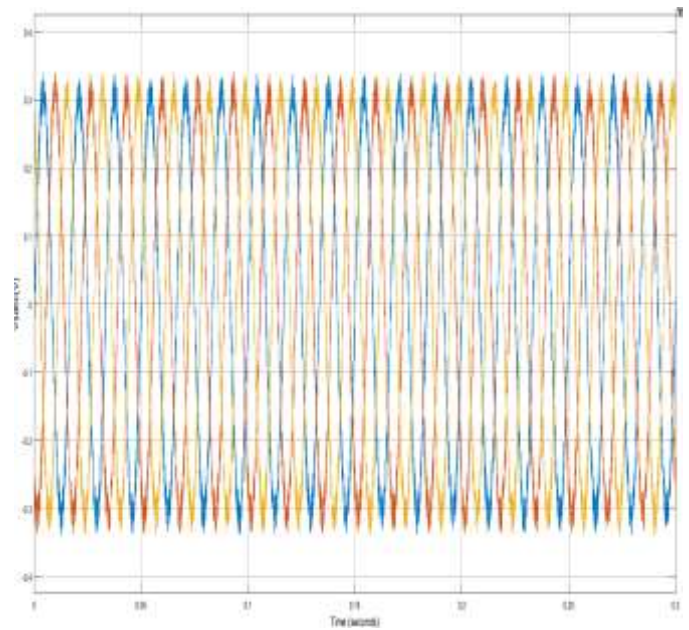


Fig.4.This plot shows a three-phase voltage waveform (V_{abc}) over a time period of 0.3 seconds.

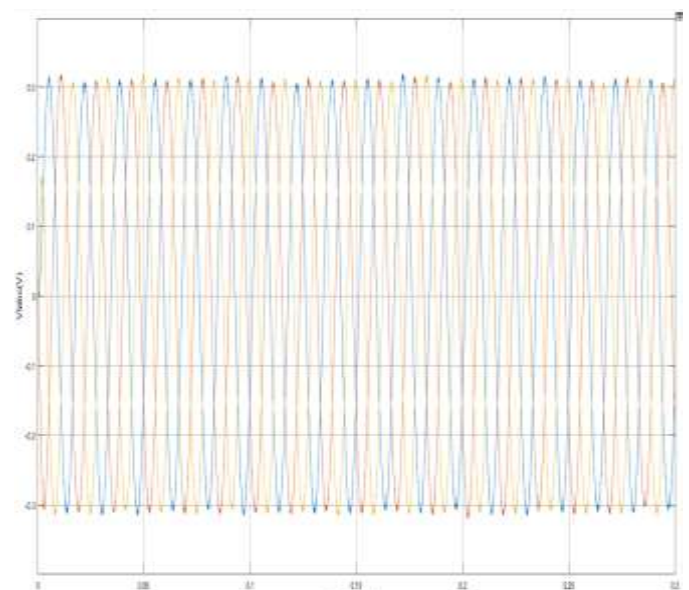


Fig.5.Three phase out put currents

This image shows a three-phase alternating current (AC) voltage waveform plotted over time. It is a typical output graph from simulation software like MATLAB/Simulink, commonly used to analyse electrical power systems or motor drives.

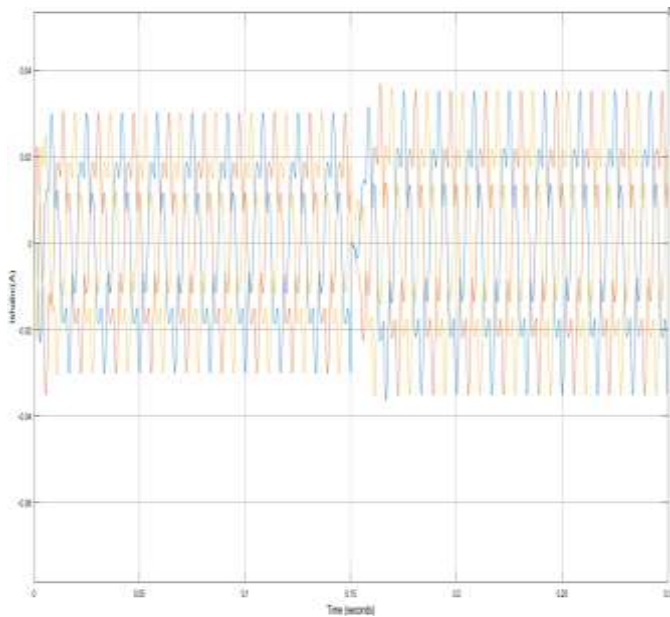


Fig.6. Three-phase source current

This plot shows the three-phase source current waveform (I_{abc}) in amperes (A) over a time span of 0.3 seconds. Based on the previous systems we discussed, this plot captures how the grid current responds to a dynamic event.

3. CONCLUSIONS

This study pioneered the use of UPQC in a wave energy-driven PMSG system for power quality improvements. Various fault and harmonics cause PQ issues in the proposed system. An enhanced control scheme of the UPQC is proposed to mitigate the PQ issues. A three-phase FFSOGI-QT1-PLL is proposed to fast and accurately extract the fundamental frequency component of the load current for use in the control of parallel converter while single-phase FFSOGI-QT1-PLL has been utilized to identify voltage faults with the series converter control at the generator side. The test results of this method compared to the methods in the literature show that the proposed method stands out better against source voltage faults, unbalanced and highly inductive non-linear various load conditions. In comparison to traditional PI, a new N-PI for the DC-bus voltage control is adopted to provide better tracking performance with lower voltage errors/oscillations, to suppress voltage overshoot and to accelerate the start-up process of the system dynamics. With the proposed control method of the parallel compensator, the DC-bus voltage deviation is kept with $0.2 V \sim 0.5 V$, the THD of the source current in all cases is kept around $1.5 \sim 2.0\%$, and the THD of the load voltage is less than 1.0% complying with the IEEE standard. Control system presented in this work enhance the dynamic performance of the system under voltage conditions at the generator side and sudden load change. Comprehensive validation results are provided to demonstrate the advantages of the proposed approach over the conventional counterpart.

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