Intelligent Predictive Control of a Battery-Assisted Unified Power Quality Conditioner for Photovoltaic Distributed Generation Systems

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Abstract: ***The proliferation of photovoltaic (PV) systems connected to power distribution networks has brought new challenges, such as harmonic distortions, voltage fluctuations, and a decline in power quality (PQ). An innovative control mechanism for distributed generating systems and Unified Power Quality Conditioners (UPQCs) driven by photovoltaic (PV) technology is detailed in this article. Consistently providing sensitive loads while simultaneously improving voltage and current quality is the goal of the proposed method. The UPQC's battery system is designed to assist in the case of a power loss, and it uses cutting-edge predictive control technology to safeguard against power outages, harmonic disturbances, and load imbalances. According to simulation studies, the proposed control strategy not only improves PQ indices but also achieves optimal energy management while reducing total harmonic distortion (THD). One possible benefit of this control method for contemporary distributed energy networks is the integration of PV production with a battery-backed UPQC.***

Keywords_ Power quality, distributed generation, predictive control, total harmonic distortion, photovoltaic (PV) systems

I. INTRODUCTION

The rapid increase in worldwide electricity consumption and the detrimental environmental impacts of power generation from fossil fuels have made clean and sustainable energy solutions more critical than ever before [1]. Conventional thermal power plants, which crank out energy by incinerating fossil fuels, are a big contributor to global warming and other serious environmental crises [2]. Solar, wind, hydro, and biomass power plants are examples of renewable energy sources (RES) that may generate electricity in a sustainable and ecologically friendly way, which is a growing concern [3]. Modular design, cheap running costs, silent operation, and scalability in deployment size (from individual roofs to enormous solar farms) are some of the most attractive features of solar photovoltaic (PV) systems [4]. In order to enhance energy availability, stability, and resilience, power networks that are either connected to the grid or run autonomously are progressively integrating PV-based distributed generating systems [5]. Operational issues caused by solar irradiation's intermittent and variable nature include voltage variations, harmonic distortions, and a general reduction in power quality (PQ) [6]. The power-generating capacity of photovoltaic panels is affected by variables such as temperature, shadow, and sunlight intensity. Because of this unpredictability, the grid is unstable, and sensitive loads are also impacted [7]. Nonlinear loads, including rectifiers, power electronic devices, variable frequency drives, and reactive power imbalances significantly reduce PQ [8]. Integrating a battery energy storage system (BESS) into a PV-based DG system is a typical way to assure a continuous power supply and offset the consequences of PV intermittency [9]. In addition to storing excess energy during periods of high irradiance, this helps to balance power generation and stabilise voltage during times of low light or night [10]. In addition, BESS has the potential to aid in voltage management, transient responsiveness, and frequency support under a variety of load circumstances [11]. However, even with these advantages, synchronising the PV source, BESS, grid, or local loads remains a significant challenge, especially when PQ pauses occur simultaneously in the voltage and current waveforms [12].

Modern power electronics have allowed for the development of specialist power devices that address power quality concerns in distributed generation environments. Among the greatest and most comprehensive devices in this category is the UPQC [13]. A UPQC employs a single DC-link capacitor for series compensation and shunting with the help of a Voltage Source Inverter (VSI) [14]. Different types of voltage source interferences (VSIs) address different voltage-related issues, such as sags and imbalances. The first kind of VSIs deals with reactive power utilisation, harmonic distortions, and load current imbalances [15]. By coordinating the operation of these two converters, UPQC ensures that critical loads are supplied with clean, steady power and that the source voltage and load current remain balanced and sinusoidal [16]. Combining it with sophisticated control and energy management, together with renewable energy sources like photovoltaics, could significantly improve its performance. When solar production is erratic or low, the battery system can still maintain the DC-link even though the output of the PV array may directly support the DC-link voltage of the UPQC in a PV-based DG system [17]. Regardless of the PV output, PQ correction will continue to function correctly with this configuration. By combining PV generation, BESS, and UPQC into a robust hybrid framework, PQ issues may be resolved and distributed energy systems can be effectively controlled [18]. But UPQC's actual power is in its control method, which controls the battery system's use and the series and shunt inverters' interaction with one another. Conventional methods such as the synchronous reference frame (SRF) and the instantaneous pq theory are commonly used to manage the current and voltage in UPQC systems [19]. Even when dealing with balanced linear loads, these methods fail miserably when applied to nonlinear or imbalanced loads, and they fail to eradicate high-order harmonics [20]. Multiple proportional-resonant (PR) and proportional-integral (PI)controllers, whose performance deteriorates at various frequencies, are equally crucial to these systems [21].

To address these concerns, researchers have looked at complex control systems that rely on artificial intelligence and model-based optimisation. Annotated neural networks (ANNs) and fuzzy logic control (FLC) based algorithms have shown greater resilience and adaptability when faced with nonlinearities [22]. However, these methods aren't very useful for real-time applications because to their high processing needs, large training datasets, and complicated tweaking [23]. Model Predictive Control (MPC) is a novel and strong alternative that has emerged; it employs real-time input and dynamic optimisation to reduce steady-state error, increase tracking precision, and speed transient reaction [24]. By minimising a preset cost function, MPC identifies the optimal control action by reducing modulation steps and tuning settings [25]. It does this by mathematically modelling the future behaviour of the system's variables. Recent years have seen a surge in interest in MPC-based control techniques for managing grid-connected renewable energy inverters, converters, and motor drive systems [26]. These techniques are able to handle nonlinear dynamics and multivariable constraints. With its prediction and optimisation capabilities, it is the ideal regulator for UPQC systems that include renewable DG sources [27]. Adding MPC to a PV-battery-supported UPQC may improve its dynamic performance, stabilise the DC-link voltage, reduce harmonics, and regulate the voltages at the source and the load [28]. Partially shaded panels, sudden shifts in irradiance, and harmonics introduced by converter switching are all potential external factors that could worsen PQ in a PV-based DG system [29]. It follows that integrating an MPC-based UPQC with energy storage might improve the efficiency of the energy flow from PV to the battery to the load. Voltage and current fluctuations may also be corrected dynamically. The control mechanism keeps the current and voltage Overall Harmonic Distortion (THD) within the limits defined by IEEE-519 [30] even under difficult scenarios.

II. EXISTING SYSTEM

Figure 1 shows a typical independent hydropower system with an integrated UPQC system. This system uses a permanent magnet switch (PMSG) to generate alternating current and has a battery backup for critical loads. Diode bridge rectifiers are examples of nonlinear loads in this setting. Using a rectifier, you may transform AC source currents into square or quasi-square waves. This self-sufficient hydroelectric power generation system with PMSG and battery backup would eventually attain better PQs if it included a UPQC to boost PQs on the load and generator ends. At each phase, the shunt VSI contacts with an inductor and is connected in parallel with the load end. Through a series transformer and interface inductor, the series VSI is linked to the generator and load terminals. Because it is directly connected to a battery storage unit, the UPQC's DC point maintains a constant voltage stability. Passive RC filters are used by both the series and shunt VSIs to decrease voltage and current ripples.

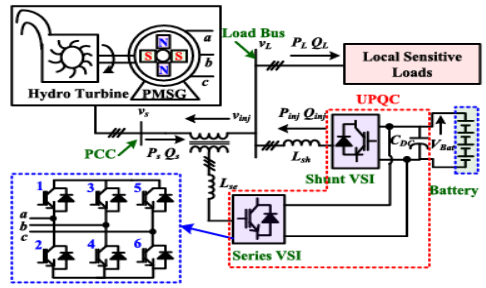


Fig. 1. Standalone hydroelectric system integrated UPQC.

III.PROPOSED SYSTEM

The suggested method for improving the voltage and current quality of the distribution network is to integrate a solar photovoltaic (PV) system, a battery energy storage unit, and a UPQC based on Intelligent Predictive Control (IPC). The PV array plays a significant role as the primary renewable energy source in the system that has been presented (Fig.2), but when solar irradiation is poor or when demand fluctuates rapidly, the battery steps in to maintain the power supply and DC-link voltage constant. A smart predictive control method is proposed for optimising the switching signals of the UPQC's shunt and series converters. It is possible to make state predictions for the system using this method in real time. A shunt compensator eliminates harmonics in the current, maintains a constant power factor on the source side, and distributes reactive power; a series compensator maintains a stable and sinusoidal load voltage in the case of voltage dips, spikes, or imbalances. With the use of battery backup and predictive management, power is distributed effectively among the PV source, load, and grid. A decrease in harmonic distortion and an improvement in transient responsiveness are the outcomes of this enhanced voltage management. According to the results of the simulations, the suggested UPQC suggestively enhances the power quality and reliability of the PV-fed hybrid energy system, while simultaneously decreasing Total Harmonic Distortion (THD) and enhancing dynamic stability.

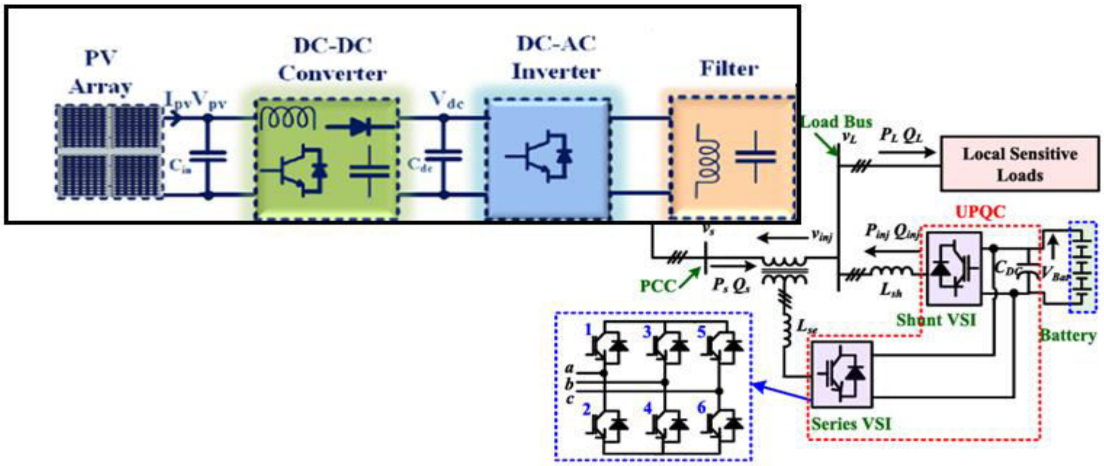


Fig.2 Proposed system Block diagram

This is the one-phase analogue of the UPQC, as seen in Figure 3. Within this schematic: The variables vL and iL, which represent the source voltage (vs) and current (is), respectively, show the voltage across the load and the current passing through it. Vsev represents the series compensator, sometimes referred to as u1. Vinjv stands for the DC voltage and injected voltage, Lse, Rse, and Cse for the LC filter losses. In this model, u2, Lsh, and Rsh stand for the filter losses, while vsh is for the shunt compensator. The ish represents the current that the shunt compensator injects to reduce the impact of the nonlinear load.

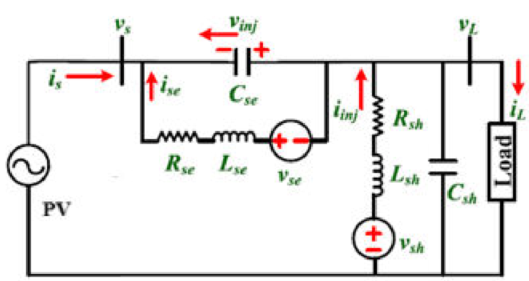


Fig.3 UPQC-integrated PV system single phase equivalent diagram.

An essential component of any UPQC, the shunt converter performs several vital tasks. Asymmetrical components and harmonic distortions in load current are the primary disturbances that it mainly aids in minimising. The overall objective is to safeguard the network against these interruptions, as stated in references [12] and [13]. The shunt converter can also be used to balance the reactive current that the load draws. However, additional compensating devices—typically passive capacitors connected in parallel with the load—manage a sizable portion of the reactive power in the load (as demonstrated in reference [14]). The ability of the shunt converter to absorb sufficient active power is another crucial feature. Refer to [15] to make sure the UPQC is operating and the DC link voltage is steady. The primary purpose of the shunt active power filter is shown in Figure 4. The main objective of the UPQC is to use an integrated series converter to deliver a reliable supply of high-quality energy. Addressing power issues including harmonic distortion, flicker, surges, voltage drops, and dips at the source is one of its many uses. Ultimately, you want the system's load side voltage to be precisely sinusoidal.

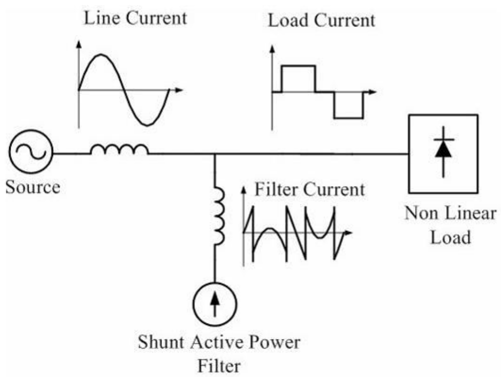


Figure 4: A shunt active power filter's basic purpose.

Furthermore, as stated in reference [6], the series converter is very successful in stabilising power systems since it decreases the chance of system-load resonance currents. The series converter can't work without the direct current (DC) connection that two series capacitors provide. In the middle of each of these capacitors is a grounded voltage reference point. They might be used as voltage sources in this configuration to aid in correction, as stated in reference [13]. Hysteresis controls the shunt converter's current output, whereas sinusoidal pulse width modulation (SPWM) controls the series converter's voltage output. You can't get a handle on how the series active power filter accomplishes these crucial tasks until you grasp the basic concept presented in Figure 6.5. Two passive filters are placed at the shunt and series converter outputs to reduce switching-induced high-frequency oscillations, as described in references [4] and [12]. The UPQC system has shunt and series transformers at the converter outputs. Converting electricity from the grid to the converters is only one of the many functions of these transformers; they also isolate the UPQC system from the main power grid. This separation is critical to the UPQC's dependable and efficient operation.

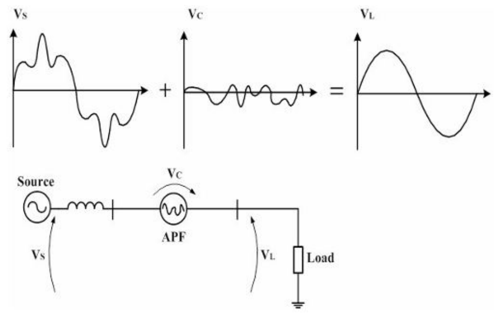


Figure 5: The functioning of a series active power filter.

Functioning Description

UPQC monitors the input voltage levels closely to guarantee regulation. If the voltage drops or rises unexpectedly, UPQC may inject or absorb reactive power to keep it constant. By using UPQC, power supply harmonics may be identified and eliminated, hence mitigating their impact.Resolving power factor mismatches allows for optimal energy efficiency. By distributing the load currents evenly over the phases, the UPQC system prevents overload. It actively monitors grid conditions using metres and sensors, allowing for continuous analysis. In the event of a disturbance or voltage shift, UPQC reacts in milliseconds. In addition to supplying a controlled voltage, a voltage source inverter (VSI) allows for the injection or absorption of reactive power. UPQC is able to quickly store and release energy because it makes use of capacitors and other forms of energy storage. The compensation parameters are continually adjusted by very powerful control algorithms in order to provide real-time control. In UPQC, safeguards are already in place to avoid harm caused by high voltage or current. Since the voltage is constant when utilising UPQC, there is less chance of a device failing or becoming damaged. Increased Reliability: It makes connected devices last longer and requires less maintenance. It is possible that UPQC may be useful in sectors like healthcare and industry that deal with fragile gear. This prevents harmonics and power fluctuations from harming data centres. Reducing energy losses is possible by optimising electricity transmission and distribution. The multifunctional UPQC is largely responsible for the increased efficiency of today's power systems. It improves the efficiency, dependability, and quality of electricity.

III. CONTROLSTRATEGYBASEDONMPC

Figure 6.6 shows the Model Predictive Control (MPC) method being used to govern a UPQC-based solo hydropower plant. A Permanent Magnet Synchronous Generator (PMSG) provides the three-phase alternating current (AC) power for this system. In the UPQC, MPC is in charge of both the shunt and series VSIs. An additional battery keeps the UPQC's DC bus voltage stable. The MPC-based control of the UPQC is designed to improve the quality of the voltage and current at the source and load terminals. There are primarily four stages to the control approach:1. For the UPQC model and state variable prediction, The second step is to put the MPC control system into action. Finding the right signals is the next thing to do. The generation of appropriate switching pulses is the fourth stage.

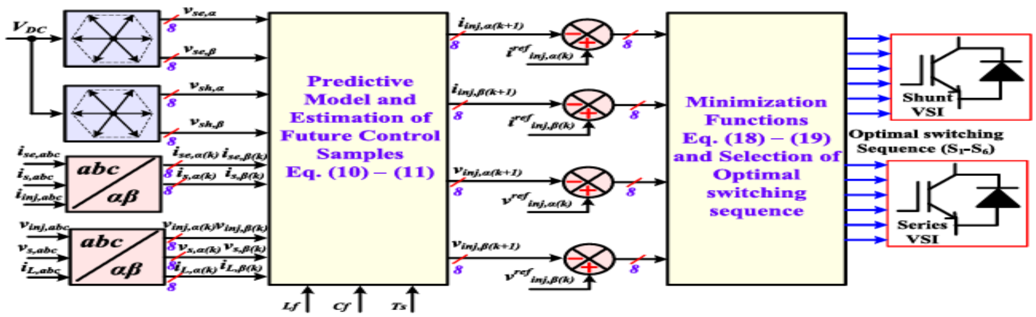
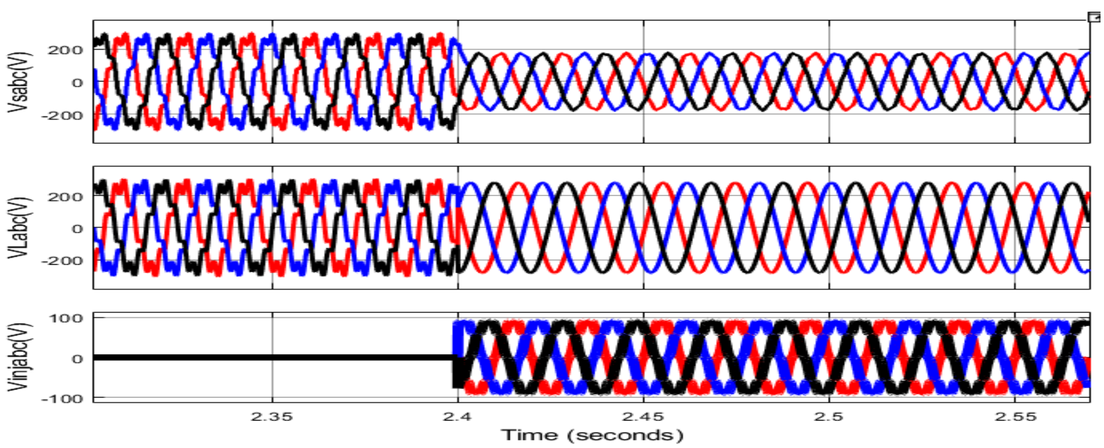
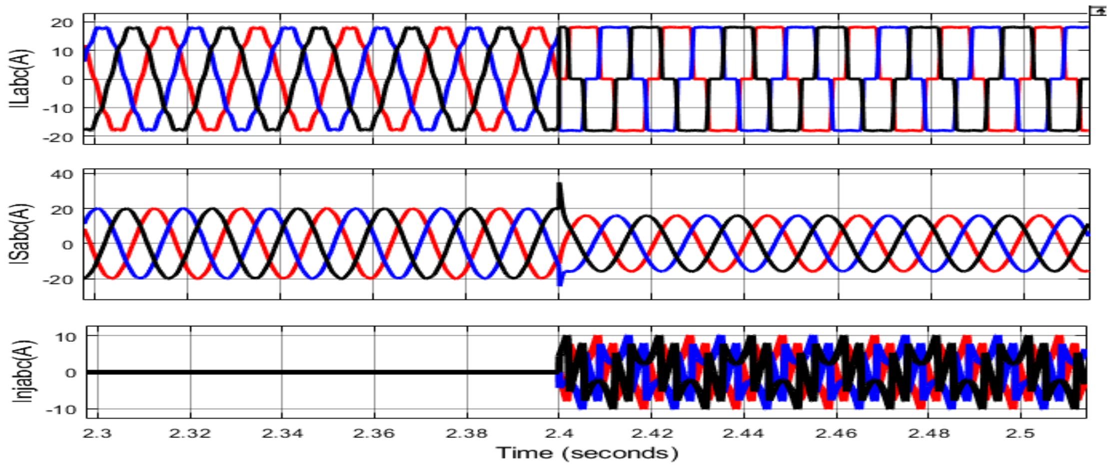


Fig.6 Diagrammatic representation of the best switching sequence estimate using model predictive control is provided.

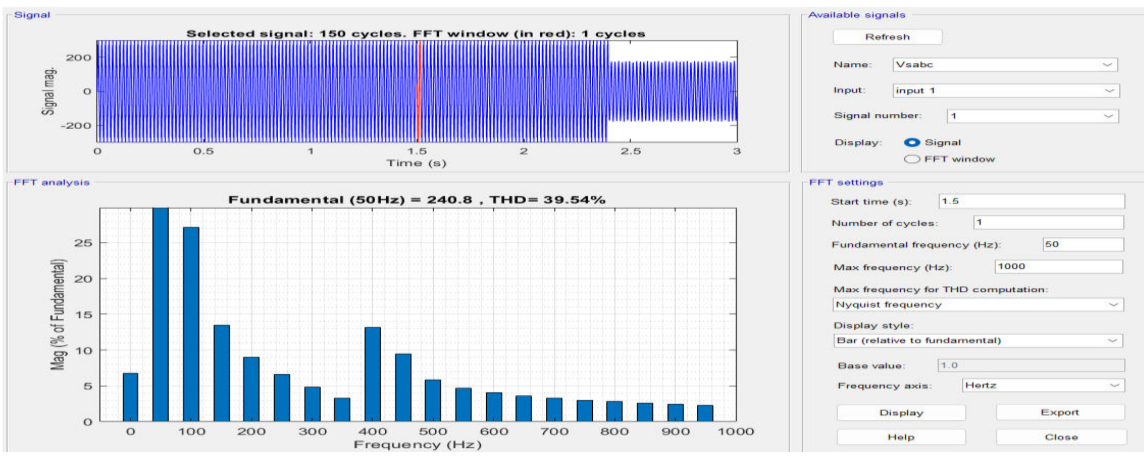
IV.SIMULATION RESULTS

A) EXISITNG RESULTS

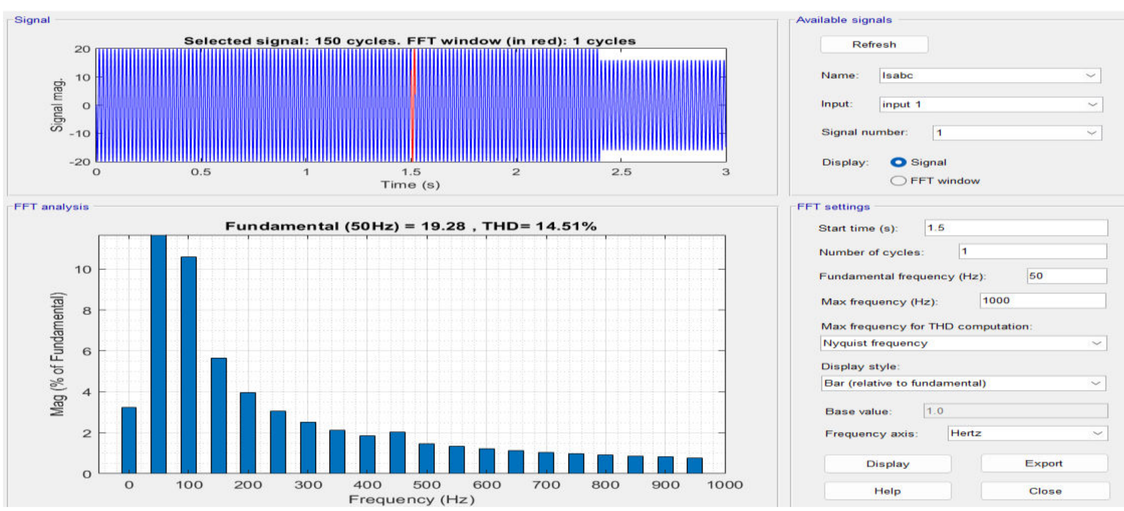



ILabc(A)
ISabc(A)
Injabc(A)
Time (seconds)

(A)


Selected signal: 150 cycles. FFT window (in red): 1 cycles
Time (s)
Fundamental (50Hz) = 240.8 , THD= 39.54%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Name: Vsabc
FFT settings
Start time (s): 1.5
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000

(B)


Selected signal: 150 cycles. FFT window (in red): 1 cycles
Time (s)
Fundamental (50Hz) = 19.28 , THD= 14.51%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
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FFT settings
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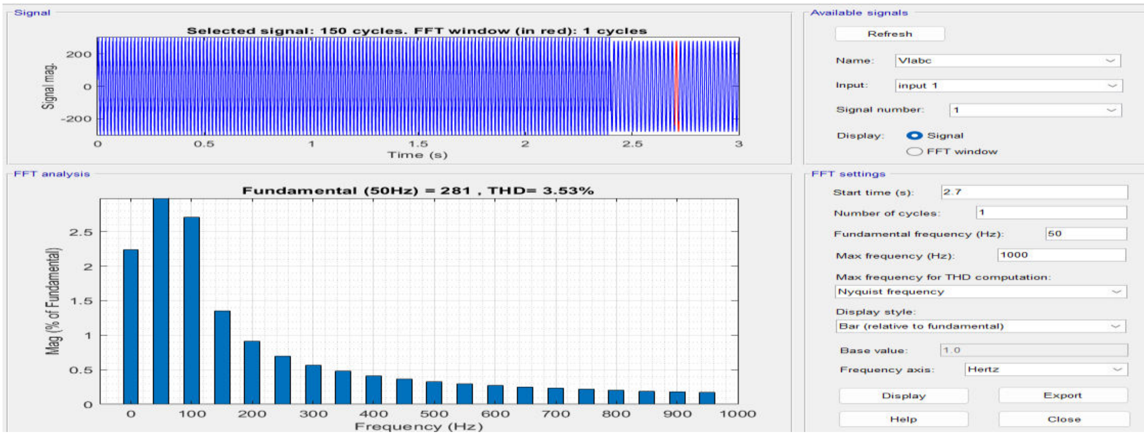
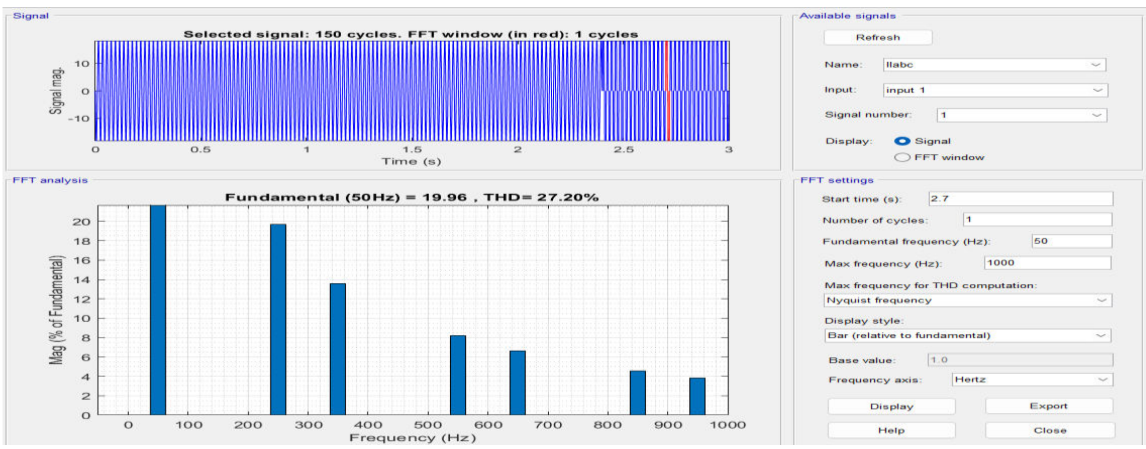
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000

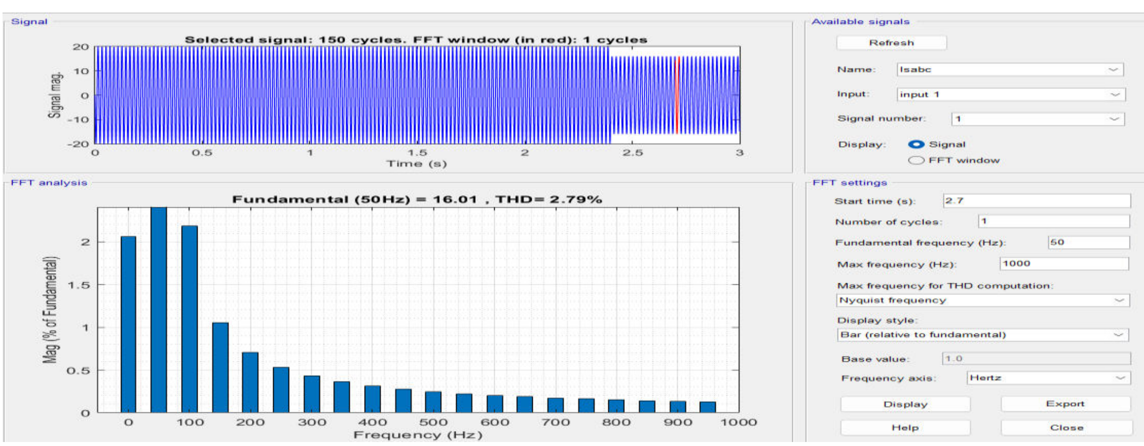
(C)



(D)

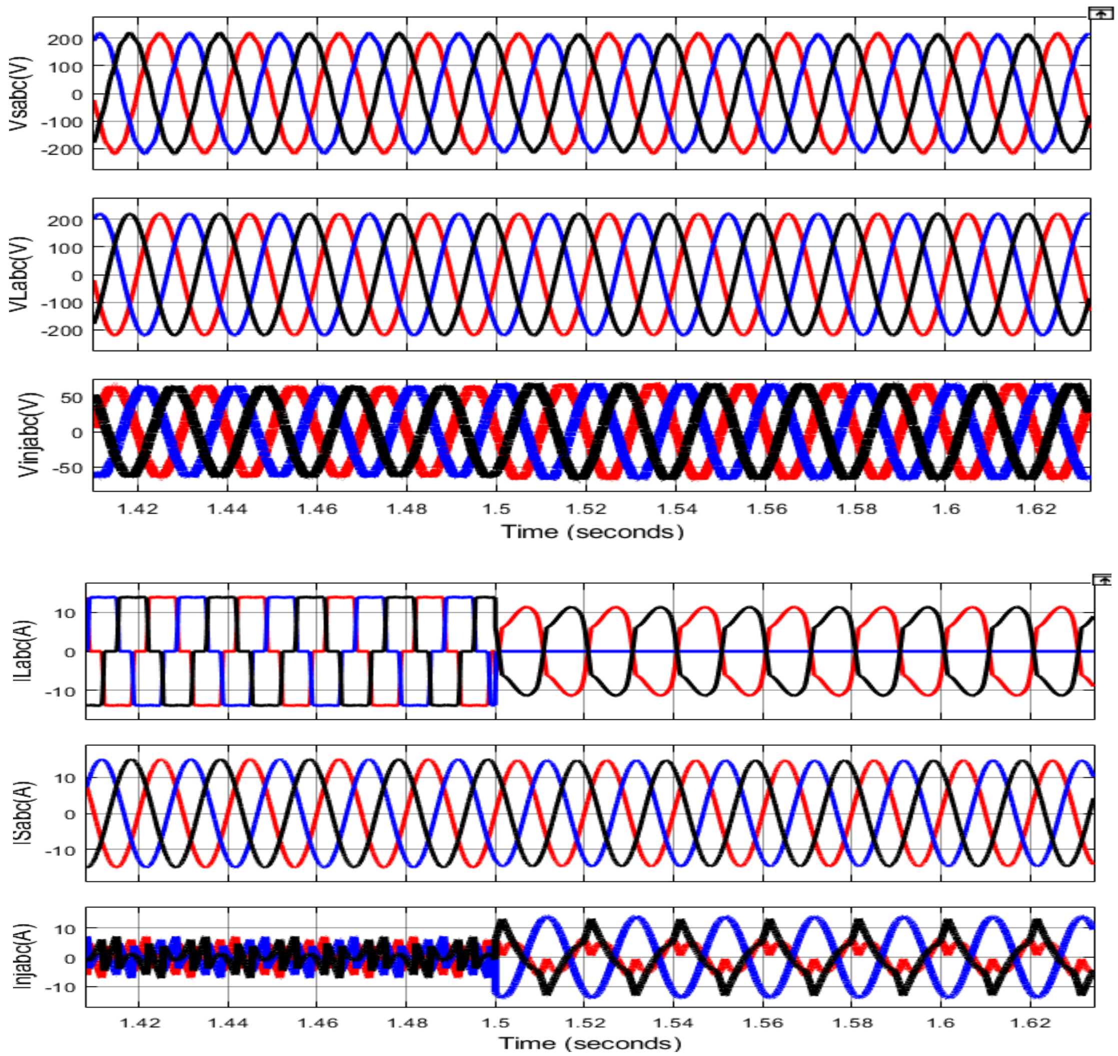


(E)

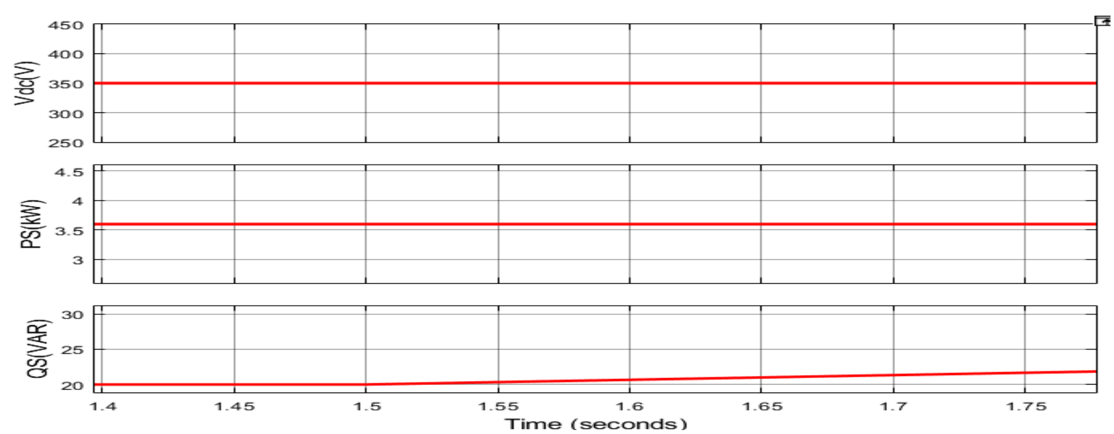


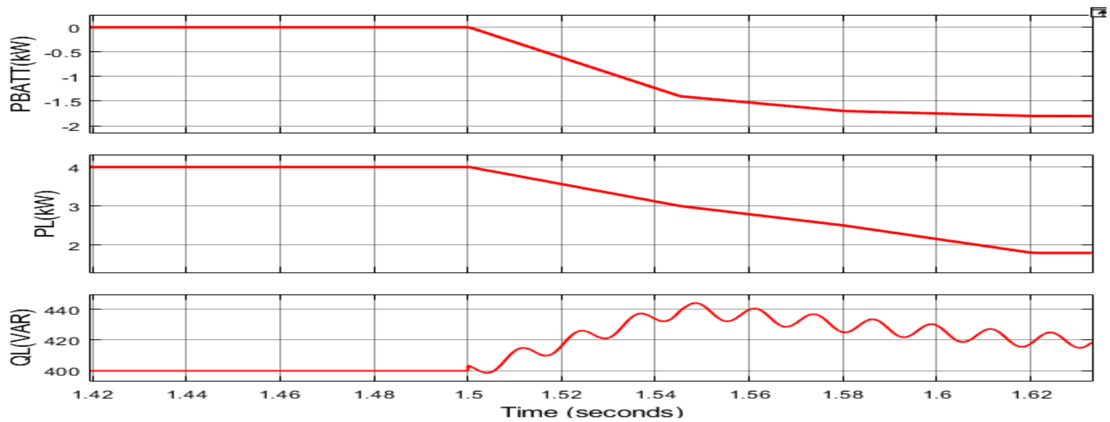
(F)

Fig 7 Compare the results of a hydropower-powered PMSG system operating alone and with and without UPQC integration. (A) vs,abc, vL,abc, vinj,anc, iL,abc, is,abc, iinj,abc(B) The THD representation of vs,a is (C) and the THD representation of vL,a is (D) when UPQC is on. And when UPQC is enabled, the THD representation for iLa is (E) and for (G) vs,a is (F).


Vsabc(V)
VLabc(V)
Vinjabc(V)
Time (seconds)
ILabc(A)
ISabc(A)
Injabc(A)
Time (seconds)

(A)

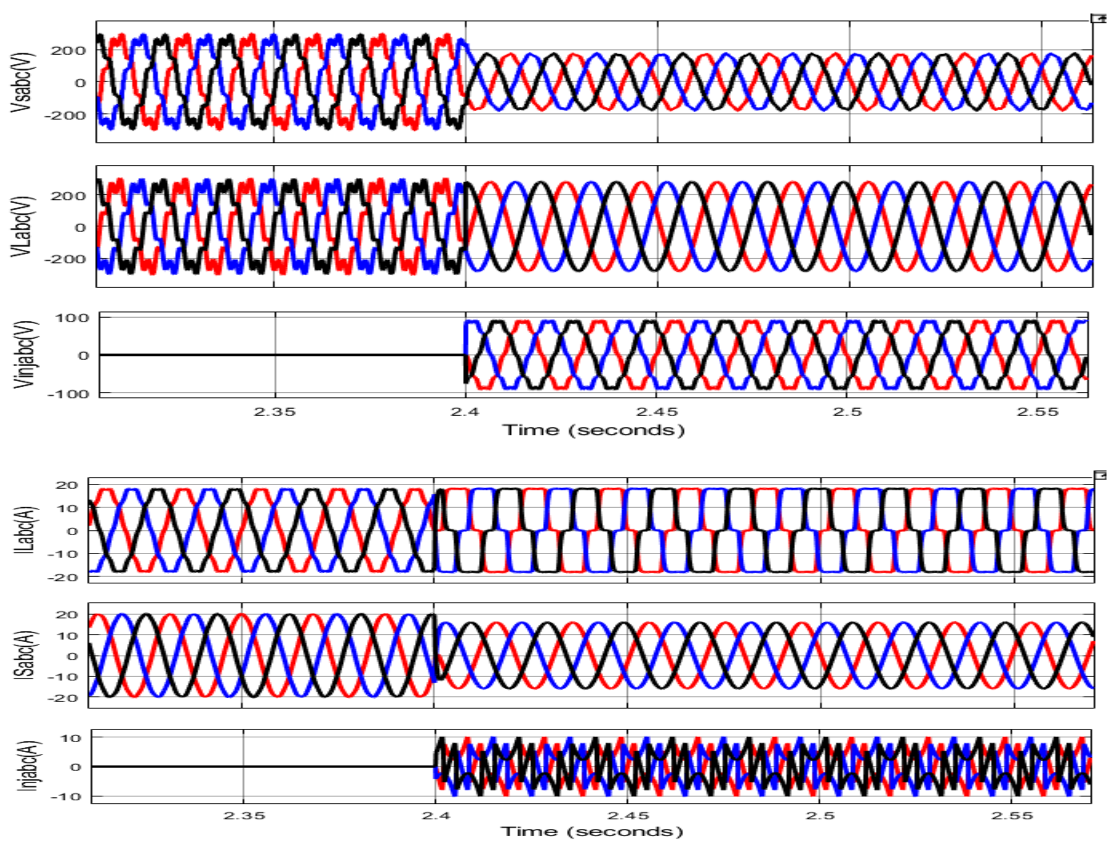

Vdc(V)
PS(kW)
QS(VAR)
Time (seconds)



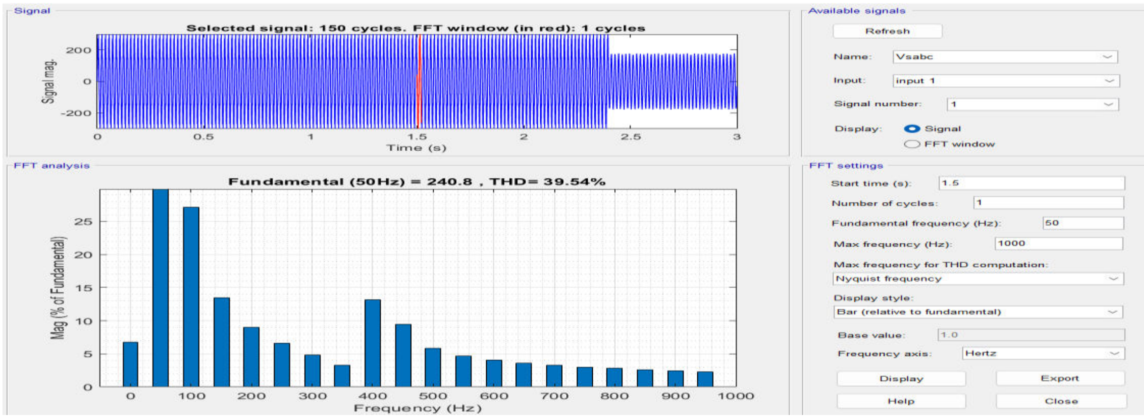
(B)

Fig.8 Actions taken dynamically when a load imbalance occurs. I shall take into account (A) vs, abc, vL, vinj, abc, iL, abc, is, abc, and iinj, abc, and (B) VDC, Ps, Qs, PBatt, PL, and QL.

B) EXTENSION RESULTS



(A)


Signal
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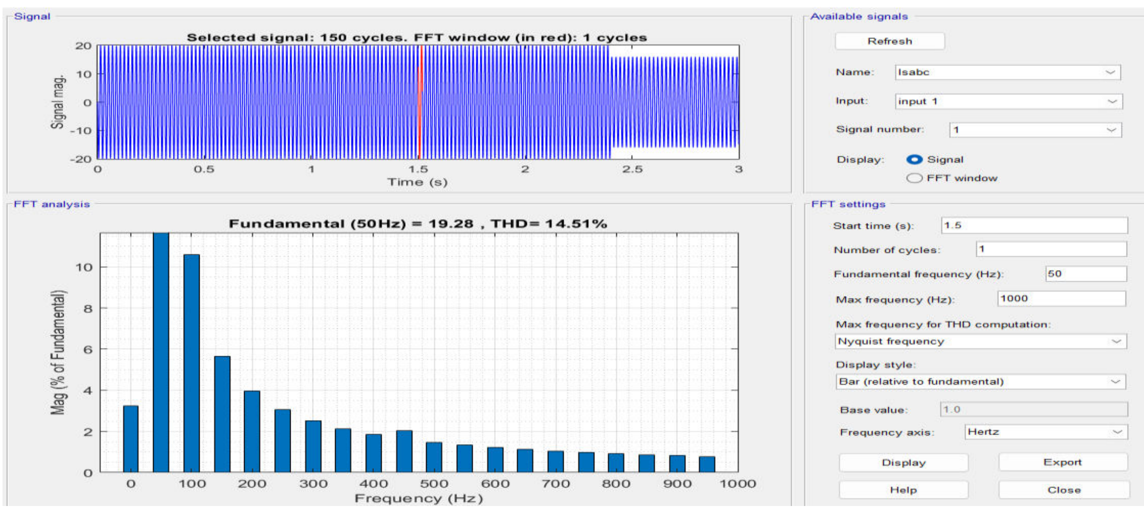
Signal mag.
Time (s)
FFT analysis
Fundamental (50Hz) = 240.8 , THD= 39.54%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Refresh
Name: Vsabc
Input: input 1
Signal number: 1
Display: Signal
FFT window
FFT settings
Start time (s): 1.5
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation:
Nyquist frequency
Display style:
Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Display
Export
Help
Close

(B)


Signal
Selected signal: 150 cycles. FFT window (in red): 1 cycles
Signal mag.
Time (s)
FFT analysis
Fundamental (50Hz) = 19.28 , THD= 14.51%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Refresh
Name: Isabc
Input: input 1
Signal number: 1
Display: Signal
FFT window
FFT settings
Start time (s): 1.5
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation:
Nyquist frequency
Display style:
Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Display
Export
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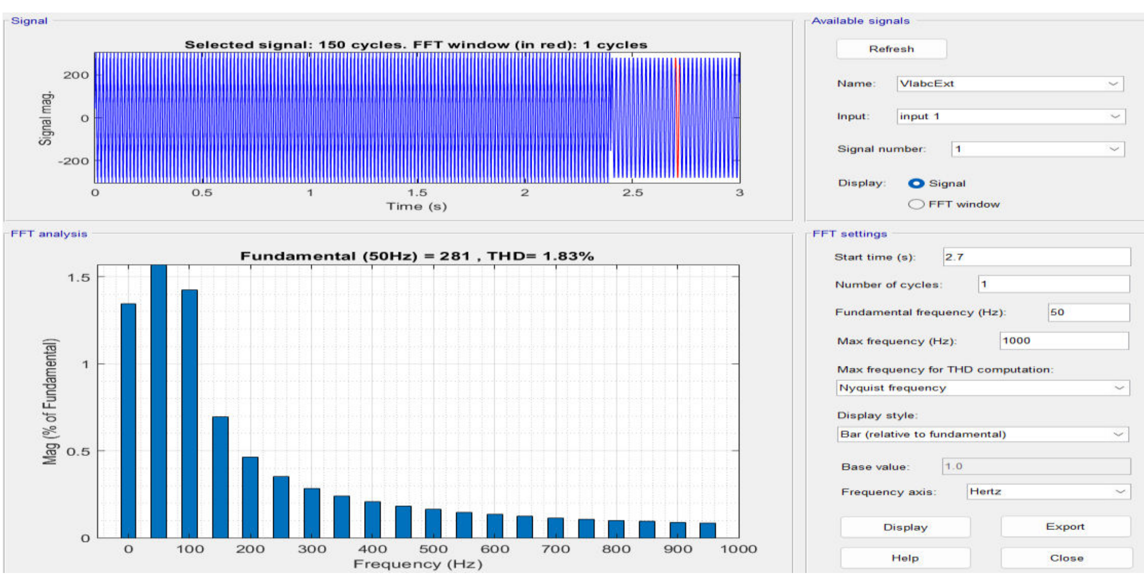
(C)


Signal
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Signal mag.
Time (s)
FFT analysis
Fundamental (50Hz) = 281 , THD= 1.83%
Mag (% of Fundamental)
Frequency (Hz)
Available signals
Refresh
Name: VlabcExt
Input: input 1
Signal number: 1
Display: Signal
FFT window
FFT settings
Start time (s): 2.7
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
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Nyquist frequency
Display style:
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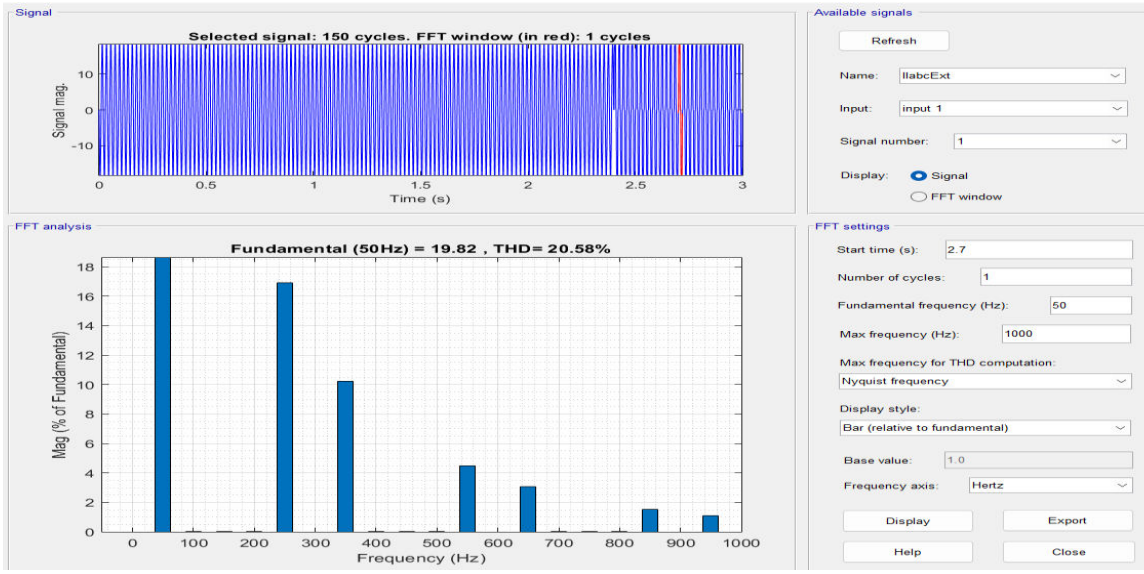
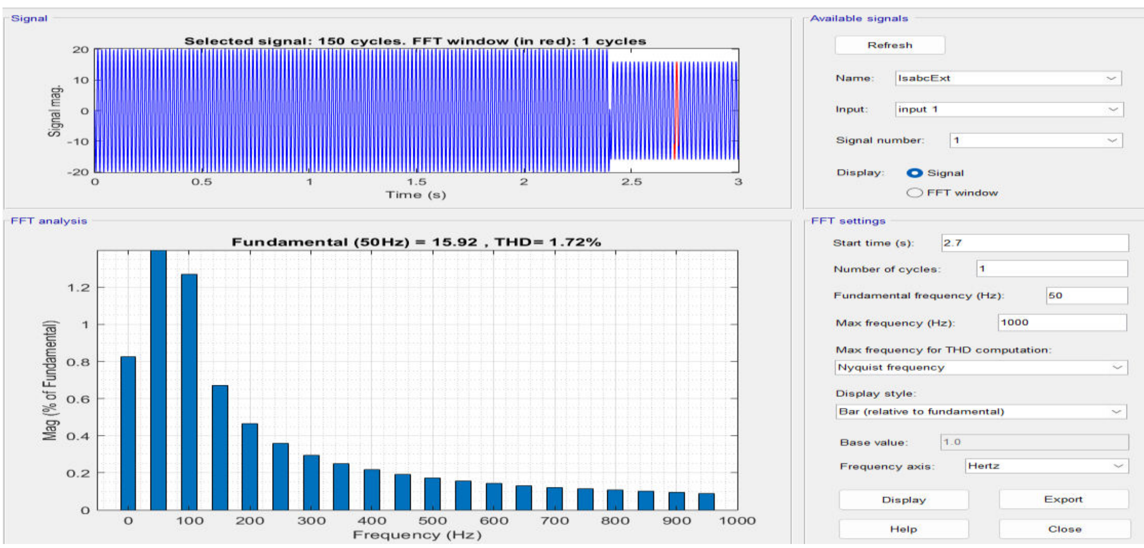
Frequency axis: Hertz
Display
Export
Help
Close

(D)

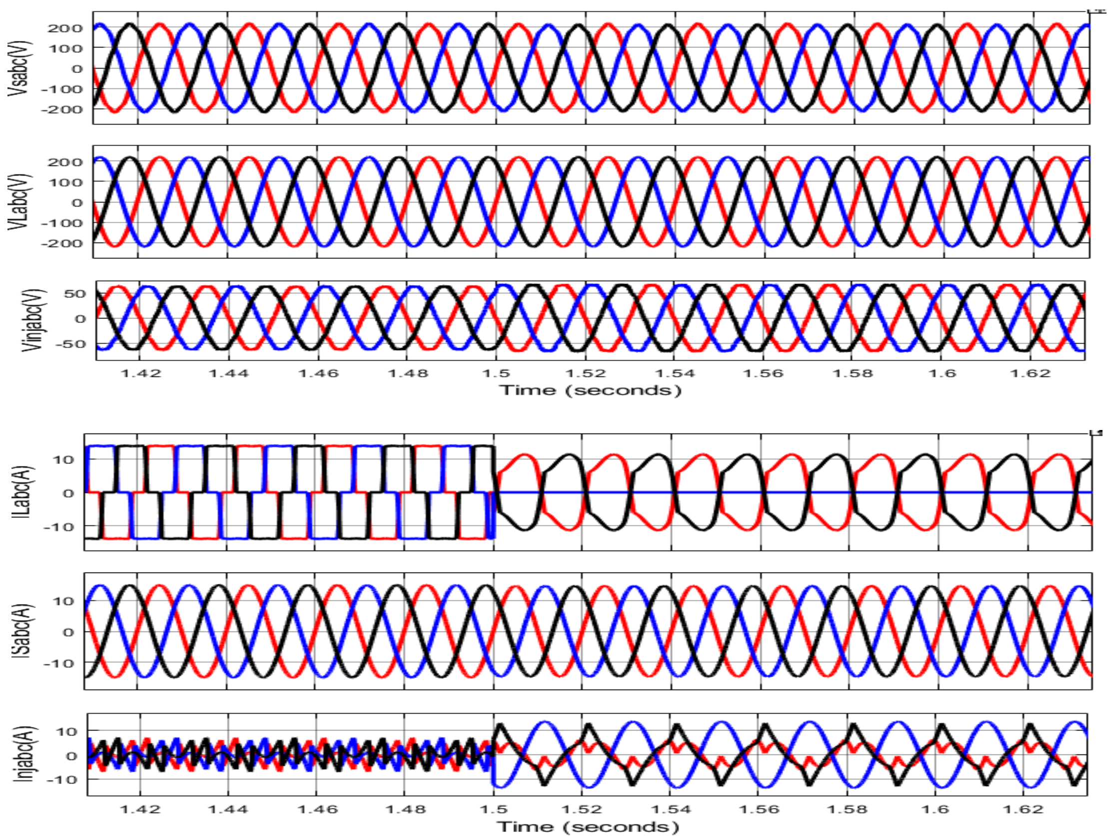


(E)

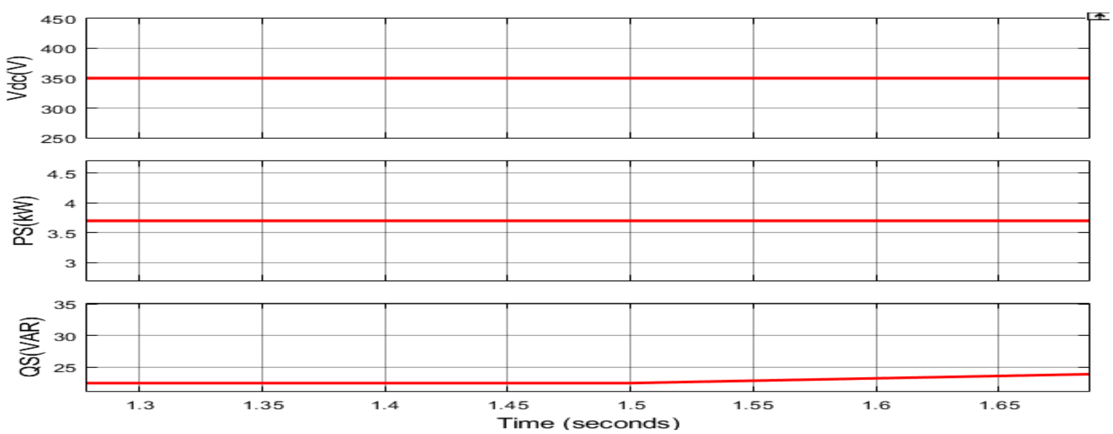


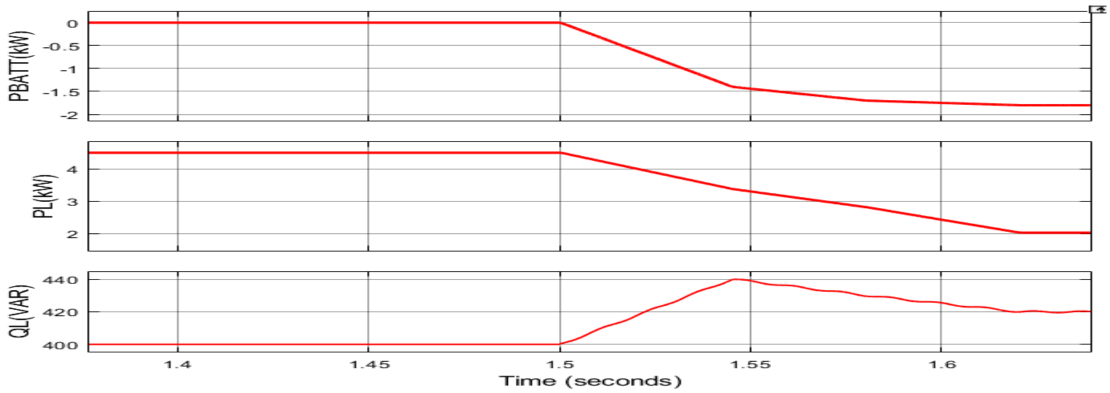
(F)

Fig.9 The outcomes of a PV system running autonomously, with or without UPQC. (A) vs,abc, vL,abc, vinj,anc, iL,abc, is,abc, iinj,abc(B) The THD representation of vs,a is (C) and the THD representation of vL,a is (D) when UPQC is on. And when UPQC is enabled, the THD representation for iLa is (E) and for vs,a is (F).


Vsabc(V)
VLabc(V)
Vinjabc(V)
Time (seconds)
ILabc(A)
ISabc(A)
Injabc(A)
Time (seconds)

(A)


Vdc(V)
PS(kW)
QS(VAR)
Time (seconds)



(B)

Fig.10 Dynamic Performance when there is a load imbalance. (A) vs,abc, vL,abc, vinj,abc, iL,abc, is,abc, and iinj,abc (B) VDC, Ps, Qs, PBatt, PL, and QL.

COMPARISION TABLE

Aspect	Existing System	Extension System
THD % in Load Voltage (vL,a) with UPQC	3.53%	1.83%
THD % in Load Current (iL,a) with UPQC	27.20%	20.58%
THD % in Source Current (is,a) with UPQC	2.79%	1.72%
Dynamic Response under Load Unbalance	Slower settling time, overshoot observed	Faster settling, minimal overshoot, stable
DC Link Voltage (Vdc) Regulation	Fluctuations during transients	Better maintained, less ripple
Power Flow (Ps, Qs, Pbatt, PL, QL)	Less stable, oscillations under sudden load	More stable, adaptive compensation

CONCLUSION

This paper examines a Model Predictive Control (MPC) technique for a UPQC that utilises a PV-based distributed generating system and a battery. This method offers excellent solutions for a variety of issues, including reactive power, load imbalance, voltage dips, harmonics, and current. In both static and dynamic operating modes, the suggested system guarantees harmonic-free PV currents and load terminal voltages. In order to stay in compliance with power quality regulations, the Total Harmonic Distortion (THD) values for PV currents and load voltages stay within the restrictions set by IEEE 519. Keeping the rated load voltage steady and running the PV system at an improved power factor both contribute to lower total system losses. When compared to traditional PMSG-based systems, the PV-based arrangement offers several benefits, such as improved efficiency, voltage control, and power quality for important loads, as shown by the validation findings.

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