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Emergency Prevention Control as a Means of Power Quality Improvement in a Shipboard Hybrid Electric Power System

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Abstract: The problems associated with the greenhouse effect have increased the desire to limit carbon dioxide (CO₂) emissions into the atmosphere, including emissions produced by shipboard electrical power systems. This has led to a further search for solutions in this area, such as shipboard hybrid electric power systems (SHEPSs). These systems do not yet have a wide application compared with traditional shipboard electrical power systems for several reasons, including the lack of studies establishing the fault tolerance of such systems. Therefore, in this work, problems related to generated power quality deterioration under large disturbances are studied. To achieve the fault-free operation of SHEPS, an emergency prevention control (EPC) system based on controlled parameter forecasting, along with a system structure and operation algorithm, is developed. The goals of improving electrical power quality are achieved by increasing the control efficiency of the power system’s generating sources. To validate the feasibility of the proposed control system, a computer simulation was carried out after developing a mathematical model of the SHEPS under study. The results of the study show that the use of the proposed EPC system will improve power quality when the controlled parameters are within acceptable limits. At the same time, further research is needed, as the problem of false control action as a consequence of EPC system hardware or software faults remains unstudied.



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Keywords: shipboard hybrid electric power system; emergency prevention control; power quality; computer simulation

1. Introduction

Increasing environmental requirements for electricity production standards [1] define the current stage of shipping development and the evolution of shipboard electrical power systems. This has led to the creation and application growth of SHEPSs, changing the principles of power distribution with a transition from traditional vertical system configurations to a distributed system approach with respect to electrical power resources. In addition, increased survivability is achieved because of the flexibility of power distribution for both shipboard consumers and generating sources.

The development of SHEPSs is driving interest in energy storage systems (ESSs) [2], which have become a key component along with traditional power sources, such as diesel generators (DGs). Furthermore, an ESS can optimize power production depending on load changes, optimizing DG fuel consumption. ESSs can be distinguished based on electrochemical, mechanical, electromagnetic, and thermal accumulators. The advantages and disadvantages of each type can be found in [3–5]. In this paper, an electrochemical system based on rechargeable batteries is considered. Additionally, the ESS relies on electrical converters to charge the batteries when a power reserve at the main switchboard (MSB) is available; the ESS can then be used as a source during a power shortage.

Because DGs have larger time constants than ESSs [6], which are based on high-performance modulation controllers (MC) and power semiconductors [7,8], the use of

traditional DGs and ESSs in shipboard electrical power systems leads to the need for a control system capable of achieving the reliable operation of SHEPS power sources in both normal and emergency modes.

To date, several papers have been devoted to research into electrical power systems in general, as well as to the study of the fault-free operation of shipboard power sources within the framework of a unified hybrid electrical power system. For example, the authors of [9] present a new control method to balance ship load demands and power generation from renewable energy systems, based on an accurate model and solutions in real conditions. The energy management system was designed and implemented in a finite state machine structure using the logical design of state transitions. The results showed that a reduction in consumption of fossil fuels is feasible, and, if this is combined with renewable energy sources, it reduces CO₂ emissions. The authors of [10] proposed an adaptive equivalent consumption minimization strategy, which was simulated and compared to the state-based and fuzzy logic energy management systems under the simulation of the real operating conditions of the ship. The paper [11] describes different marine applications of battery energy storage systems in relation to peak shaving, load leveling, spinning reserve, and load response. The researchers of [12] describe a high-fidelity benchmark for hybrid electric vessels, combining diesel generators and batteries. The benchmark consists of detailed models, the parameters of which are provided so that the models can be reproduced. The authors of [13] considered a comparison of a virtualized synchronous generator (SG) and droop control characteristics during the use of inverter-based distributed generators. Similarly, researchers in [14–16] studied the possibility of virtualizing converter operation algorithms to achieve synchronization with a synchronous generator. The above-mentioned virtualization method was adopted in this paper for the inverter-based ESS, with the aim of carrying out a simulation of DG and ESS in parallel operation.

Electrical power quality requirements are set by international standards [17] and a set of marine classification society [18] standards and requirements for electrical equipment. Various control systems, such as automatic voltage regulators (AVRs) and engine speed governors (ESGs), have been designed with the aim of generating the required power quality. These systems have a control effect on power sources through the executive elements of these systems, for example, by increasing or decreasing the diesel engine (DE) fuel supply or regulating the generator excitation based on the feedback values of the controlled parameter. However, these devices and systems cannot reliably perform their assigned functions under conditions of large disturbances [19]. In addition, the control of parameters characterizing the power quality, such as voltage and frequency, is carried out through shipboard protective automatic systems. These systems use shutdown and tripping functions to prevent the operation of electrical power system components if the controlled parameters are not within acceptable limits. Furthermore, interruption of the power supply to ship consumers can also occur, causing a possible emergency state of one scale or another.

Therefore, a control system is needed that can provide fast-acting control of SHEPS components to improve the electrical power quality. To achieve this goal, we propose a novel software- and hardware-integrated EPC system designed to perform the functions of monitoring and proactive control based on the forecasting of controlled parameters. While the basic principles involved in developing EPC systems were discussed in [20], this paper studies a particular case of DG and ESS operation as part of a SHEPS under large disturbances that occur during the direct start of the induction motor (IM). The voltage and frequency of power sources as evaluation parameters, among other parameters characterizing the electrical power quality, form the basis of this investigation.

This study was conducted in several stages, which are described in the paper in individual sections. Section 2 describes the materials and methods, where, besides the problem statement, the development of the EPC system, including system structure and operation algorithm, is discussed along with the development of the SHEPS mathematical model used for further simulation. Section 3 presents and analyzes the results of the

simulations. In Section 4, the EPC system implementation features as well as the limitations which might have had a significant impact on the results are discussed. Finally, Section 5 concludes the paper.

2. Materials and Methods

The SHEPS's EPC system, based on the forecasting of controlled parameters, is the subject of the study. Here, the computer modeling method was employed, which is a typical approach used in the study of complex system processes [21].

2.1. Problem Statement

A part of a vessel's SHEPS was taken as the initial system under study. This was one of the sections of the main switchboard operated in split bus mode of the DP3 dive support vessel. The single-line diagram of the system under study, presented in Figure 1, includes the following: a synchronous diesel generator, DG_1 , consisting of a drive diesel engine, DE_1 , and synchronous generator, SG_1 ; a synchronous diesel generator, DG_2 , consisting of a drive diesel engine, DE_2 , and synchronous generator, SG_2 ; an energy storage system, ESS, which consists of the battery pack, B, and converter, C; the thrusters' variable frequency drives, VFD_1 and VFD_2 ; the thrusters' induction motors, IM_1 and IM_2 ; the power supply system for the hydraulic pump drive motor of the electro-hydraulic crane, with a lifting capacity of 400 tons, which consist of local distribution board, DB, and induction motor, IM_3 ; and circuit breakers CB_1 , CB_2 , CB_3 , CB_4 , CB_5 , CB_6 , CB_7 , and CB_8 .

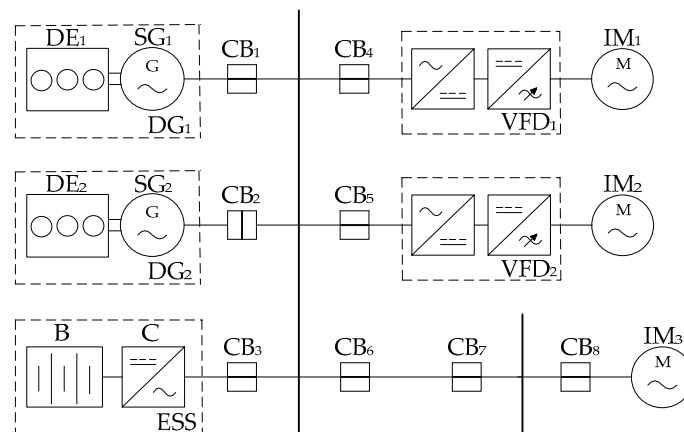


Figure 1. Initial single-line diagram of the system under study.

The vessel operation mode is assumed as follows:

- The vessel is considered as being operated offshore with calm seas where the thruster load does not exceed 5% and does not have a significant effect on the total consumption load and, thus, is not considered further.
- Synchronous diesel generator DG_2 is assumed to be offline as a standby power source and is therefore also not considered.

Based on the above-mentioned assumptions, the single-line diagram of the system under study is presented in Figure 2.

The single-line diagram of the system under study, presented in Figure 2, includes the following: synchronous diesel generator, DG, which consists of drive diesel engine DE and synchronous generator SG; main switchboard MSB; local distribution board DB; circuit breakers CB_1 , CB_2 , CB_3 , CB_4 , and CB_5 ; induction motor IM; energy storage system ESS, which consists of the battery pack, B; and converter C.

The basic parameters of the system's key elements are presented in Table 1, where P_{sgnom} , P_{imnom} , and P_{essnom} are the SG's, IM's, and ESS's nominal active power values, respectively; U_{sgnom} , U_{imnom} , and U_{essnom} are the SG's, IM's, and ESS's nominal voltage values, respectively; and E_{nom} is the ESS battery pack's nominal capacity value.

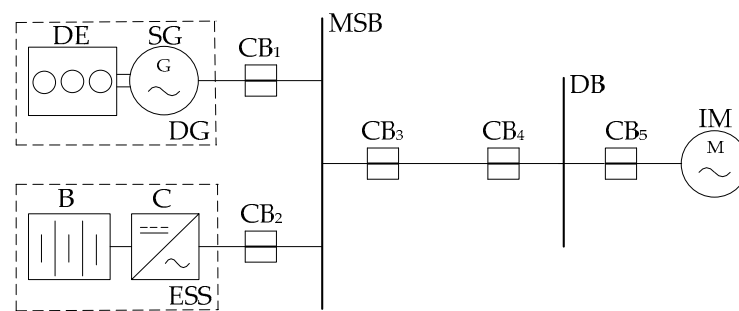


Figure 2. Single-line diagram of the system under study.

Table 1. Parameters of key elements of the system under study.

System Component	Parameters
Synchronous generator	$P_{sgnom} = 1900 \text{ kW}$, $U_{sgnom} = 690 \text{ V}$
Induction motor	$P_{imnom} = 735 \text{ kW}$, $U_{imnom} = 690 \text{ V}$
Energy storage system	$P_{essnom} = 1800 \text{ kW}$, $U_{essnom} = 690 \text{ V}$, $E_{nom} = 1415 \text{ kWh}$

During the direct start of the IM (Figure 1), an inrush current creates a braking torque for the DG and ESS, leading to a deterioration in the power quality, with deviations in frequency and voltage from nominal values. Thus, the developed SHEPS EPC system must realize an improvement in power quality.

Currently, various protection devices [22,23] are widely used to determine the degree of power quality, allowing operation if the controlled parameters (voltage and frequency) of the parallel-operating power sources are within acceptable limits. Depending on the levels of deviation of the controlled parameters, these devices form control signals to disconnect the power source from the MSB, resynchronizing it or unloading the power sources by tripping non-essential consumers. In these cases, the uninterrupted power supply to the power consumers is not guaranteed, leading to partial or complete blackout, a major disadvantage of such systems.

Practically, consumer start block methods are widely used if the available reserve power at the MSB is below a certain threshold. However, additional costs are associated with the installation of additional power sources at the design stage of the SHEPS. Moreover, starting reserve power sources will lead to an increase in emissions, which, along with the cost of the fuel, will decrease the equipment's lifetime.

To solve this problem, the development of a SHEPS EPC system that can increase the control and management efficiency of the power system is proposed. The efficiency increase is introduced through the formation of a proactive EPC signal and is implemented via secondary control channels for the SHEPS power sources.

2.2. Development of SHEPS EPC System

The DG and ESS have different physical features, which are based on different principles of power generation. Despite this, the SHEPS's components, as technical objects, are controlled via mode parameters, and the transient processes in this case can be controlled through a set of parameters that change according to certain laws. Therefore, the information characteristics of the ongoing processes can be presented in the form of a vector, $x_{ij} = (x_{ij1}, x_{ij2}, \dots, x_{ijn})$, which uniquely represents a technical object's mode, j , at fixed times, i . After normalizing the input data [24], the vector of normalized parameters, $x_{ijN} = (x_{ij1N}, x_{ij2N}, \dots, x_{ijnN})$, describes a certain trajectory that allows us to study the behavior of the object and to determine the state and mode of operation.

The proposed EPC system is based on a central processing unit (CPU) that forms the vectors of proactive control for SHEPS power sources via secondary control channels based on the forecasted values of the controlled parameters. The implementation of forecasting is

proposed based on using the first and second derivatives of the controlled parameters [20], which describe controlled transient processes. In this case, the first and second derivatives are the speed and acceleration of the controlled parameter change, respectively, as shown by Equation (1).

$$\lambda_{ij\ n} = f\left(\frac{dx_{ij\ N\ n}}{dt}, \frac{d^2x_{ij\ N\ n}}{dt^2}\right) \quad (1)$$

In Equation (1), $\lambda_{ij\ n}$ is the output function of the controlled parameter forecasted values; $x_{ij\ N\ n}$ are the normalized parameter values. Consequently, the vector of the forecasted values of the controlled parameters can be represented as $\lambda_{ij} = (\lambda_{ij\ 1}, \lambda_{ij\ 2}, \dots, \lambda_{ij\ n})$.

However, while using derivative links in control laws, a problem occurs, which is associated with the loss of an output signal (equal to zero) when a controlled parameter becomes a constant value [20]. Therefore, the control law based on the first and second derivatives is supplemented with a third component that characterizes traditional control algorithms. This component is based on the normalized measured values of the controlled parameters. Thus, the control signal is based on the generalized parameter, σ_{ij} , which is formed as a sum of the normalized controlled parameter, $x_{ij\ N\ n}$, and its first, $\frac{dx_{ij\ N\ n}}{dt}$, and second, $\frac{d^2x_{ij\ N\ n}}{dt^2}$, derivatives, as per Equation (2).

$$\sigma_{ij\ n} = K_2 \frac{d^2x_{ij\ N\ n}}{dt^2} + K_1 \frac{dx_{ij\ N\ n}}{dt} + K_0 x_{ij\ N\ n} \quad (2)$$

In Equation (3), K_0 , K_1 , and K_2 are the proportionality coefficients.

Considering Equations (1) and (2), the control law can be expressed by Equation (3).

$$y_{ij\ n} = f\left(\frac{d^2x_{ij\ N\ n}}{dt^2}, \frac{dx_{ij\ N\ n}}{dt}, x_{ij\ N\ n}\right) = f(\sigma_{ij\ n}) \quad (3)$$

Thus, the EPC control vectors take the form $y_{ij} = (y_{ij1}, y_{ij2}, \dots, y_{ijn})$.

The calculation and formation of the EPC vector can be represented as a block diagram, as shown in Figure 3.

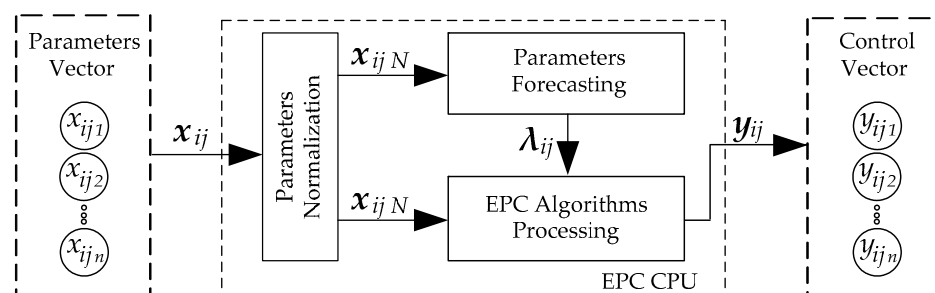


Figure 3. Block diagram of EPC vector formation.

Because the derivative of a constant is zero, the secondary control channel does not significantly impact the control of DG and ESS in the SHEPS' normal operating mode when the speed and acceleration of the changes in the controlled parameters are within acceptable limits. In other words, since the formed EPC vectors are based on mathematical models and physical properties of the DG's and ESS's local control systems, in normal mode, the EPC system duplicates traditional control algorithms. Thus, by assessing the speed and acceleration of changes in the controlled parameters, we can forecast and anticipate emergency state and fault conditions.

Figure 4 shows the block diagram of the EPC system at any time, i , of mode j for the SHEPS under study, where $x_{ij\text{ DG}} = (\omega_{ij\text{ DG}}, U_{ij\text{ DG}})$ and $x_{ij\text{ ESS}} = (\omega_{ij\text{ ESS}}, U_{ij\text{ ESS}})$ are the EPC system input vectors, defining the controlled parameters of DG and ESS, respectively.

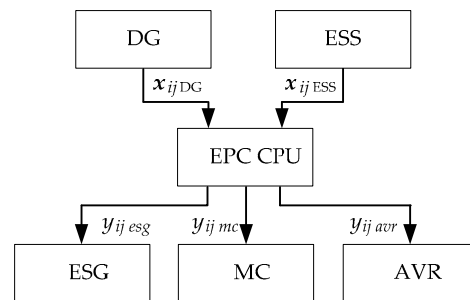


Figure 4. Block diagram of the SHEPS EPC system.

By monitoring the parameters of the SHEPS's elements (Figure 4), the EPC system can determine the speed and acceleration of controlled parameter changes. This allows us to determine the pre-fault mode and subsequent deviations in the power system voltage and frequency and, using the secondary control channels, provide proactive actions via the local control actuators of the power sources, such as increasing/decreasing the DE fuel supply, regulating the field excitation of the SG, and changing the modulation coefficients in the control circuits of the ESS inverter. Thus, using the controlled parameter vectors of the SHEPS's elements, the EPC system is designed to monitor and improve the power quality by calculating and forming the EPC control signals (Figure 3) as follows:

- The ESG's control signal, $y_{ij\text{ esg}}$.
- The control signal for the ESS's MC, $y_{ij\text{ mc}}$.
- The AVR's control signal, $y_{ij\text{ avr}}$.

These control signals form the EPC vector $y_{ij} = (y_{ij\text{ esg}}, y_{ij\text{ mc}}, y_{ij\text{ avr}})$ and provide proactive control for the local actuators of the power sources via secondary control channels, allowing us to improve the power quality of the SHEPS. Based on the above, increasing the control efficiency becomes possible by implementing controlled parameter forecasting in the control laws.

2.3. SHEPS EPC Algorithm

The SHEPS is characterized by multi-component, multi-mode, and multi-functional elements. General tasks and a common goal of the SHEPS operation help to form a generalized control algorithm, the peculiarity of which is the following set of subtasks, which should be solved by the automatic (automated) control system:

- Collection of SHEPS information;
- Processing of collected information according to specified and newly formed algorithms, determined by the state of the SHEPS and the EPC system;
- Forming of monitoring and control signals.

The specification of individual tasks allows us to consider the general operating algorithm as a set of particular algorithms executed in a certain time sequence and a prioritized functional relationship, implementing the common information processing task in the required direction with the preset accuracy and discreteness for control signal formation.

The generalized algorithm (Figure 5) can be represented by a flow diagram, which includes the following sub-algorithms:

1. Algorithms for complex processing of input data. The optimization of input data processing is based on eliminating their redundancy to increase the accuracy and reliability of the input parameter assessment. It is implemented as time- and function-dependent processing.

2. Algorithms for control tasks of the SHEPS (functional algorithms). This set of algorithms is for control tasks determined by the power system tasks, which reflect the composition of input data, control, and monitoring interfaces. These algorithms determine the main characteristics of the entire power system.
3. Algorithms for diagnosing the technical condition of the SHEPS, protecting the functional algorithms. These consist of test algorithms and performance monitoring and allow us to check the performance of equipment by testing under known conditions and to determine the location of faults.
4. A forecast processing and management control algorithm based on the forecast results. This algorithm provides preparatory measures, for example, by turning off potentially faulty equipment in advance or turning on redundancy power sources. Based on the analysis of the possible fault scenarios or changes in the nature of the processes ongoing in the SHEPS operation, the algorithm prevents emergency modes and conditions. In addition, it provides the formation of control actions on changes in the state of SHEPS elements and modes to prevent the transition of the entire power system to the pre-fault area of operation.
5. Algorithms for EPC tasks. These allow us to detect and correct errors in the control algorithms and forecast and prevent fault states and emergency conditions.

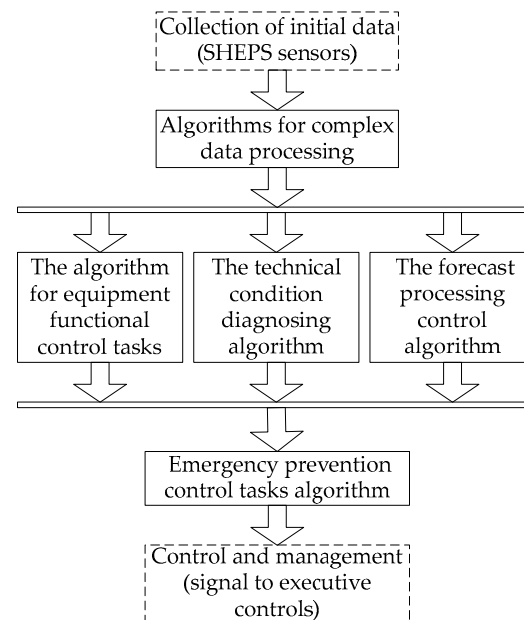


Figure 5. SHEPS generalized control algorithm.

Sub-algorithms 3–4 are parallelly processed for organizing the computational work of a given application such that multiple parts of the workload can be performed concurrently to reduce the time to a solution and increase performance.

Analysis of the algorithm flow diagram (Figure 4) identifies the necessary control actions to achieve reliable operation of the SHEPS. To enable automated control systems to solve the above tasks, they, in addition to subsystems for localizing the fault and restoring normal operation, must include algorithms that implement EPC based on the forecasting of the controlled parameters.

2.4. Mathematical Model of SHEPS under Study

For further study of the proposed solution's feasibility, computer modeling was carried out. A mathematical model of the SHEPS under study, presented in Figure 1, was developed for this purpose.

2.4.1. Model of Diesel Engine and Engine Speed Governor

The IEEE general model for drive engines and speed governors presented in [25,26] was adopted as the basis for this study. The mechanical motion in proportional units is expressed by the nonlinear differential equation, Equation (4).

$$\frac{d\omega_{DG}}{dt} = \frac{1}{\tau_{de}}(T_{Dm} - T_{De}), \quad T_{Dmmin} \leq T_{Dm} \leq T_{Dmmax} \quad (4)$$

In Equation (4), ω_{DG} is the DG frequency; τ_{de} is the DG time constant; T_{Dm} and T_{De} are the mechanical torques of the DE and SG, respectively; and T_{Dmmin} and T_{Dmmax} are the maximum and minimum DE torque values, respectively. Differential equations describing the ESG can be represented by a system, as per Equation (5):

$$\begin{cases} \frac{dT_{Dm}}{dt} = \eta_{esg} \\ \frac{d\eta_{esg}}{dt} = -\frac{\tau_c}{\tau_{se}^2}\eta_{esg} - \frac{k_c}{\tau_{se}^2}T_{Dm} - \frac{k_{act}}{\tau_{se}^2}(T_{Dm} - \varepsilon_{act}) - \frac{1}{\tau_{se}^2}\omega_{DG} \\ \frac{d\varepsilon_{act}}{dt} = \frac{1}{\tau_{esg}}(T_{Dm} - \varepsilon_{act}) \end{cases} \quad (5)$$

where η_{esg} is the fuel rack position; k_c and k_{act} are the droop coefficients of the ESG controller and the ESG actuator, respectively; τ_c , τ_{se} , and τ_{act} are the time constants of the ESG controller, sensing element, and actuator, respectively; and ε_{act} is the ESG actuator feedback signal.

2.4.2. Model of the Synchronous Generator and Automatic Voltage Regulator

For the mathematical description of the SG, Park's equations are used in the d - q coordinate system with simplifying assumptions [27,28], i.e., transformer and rotational EMFs, as well as generator saturation, are not considered. Excitation and damping windings are considered on the d -axis to reflect the corresponding transient and sub-transient time constants. Taking these assumptions into account, an SG can be represented by the differential and algebraic Equations (6)–(17). Equation (6) denotes the excitation system's winding flux linkage, ψ_f .

$$\frac{d\psi_f}{dt} = \frac{1}{\tau_{fsg}}(U_f - i_f) \quad (6)$$

In Equation (6), τ_{fsg} is the AVR time constant, and U_f and i_f are the excitation system voltage and current, respectively. The flux linkages of the damping winding along the d -axis, ψ_D , take the form of Equation (7):

$$\frac{d\psi_D}{dt} = -\frac{1}{\tau_{Dsg}}i_D \quad (7)$$

where τ_{Dsg} is the time constant of damping winding along the d -axis; and i_D is the current of damping winding along the d -axis. Equation (8) represents the flux linkages of the damping winding along the q -axis, ψ_Q .

$$\frac{d\psi_Q}{dt} = -\frac{1}{\tau_{Qsg}}i_Q \quad (8)$$

In Equation (8), τ_{Qsg} is the time constant of damping winding along the q -axis, and i_Q is the damping winding current along the q -axis. The generator voltage, U_{DG} , can be represented by the following algebraic Equation (9):

$$U_{DG} = \sqrt{U_d^2 + U_q^2} \quad (9)$$

where U_d and U_q are the voltage components along the d - and q -axes, respectively. U_d is represented by Equation (10):

$$U_d = -r_{sg}i_d + \psi_q \quad (10)$$

where r_{sg} is the active stator resistance, and ψ_q is the stator windings flux linkage along the q -axis. The voltage component, U_q , along the q -axis can be written using Equation (11):

$$U_q = -r_{sg}i_q + \psi_d \quad (11)$$

where ψ_d is the flux linkage of the stator windings along the d -axis, which can be written as Equation (12):

$$\psi_d = i_f - x_{dsg}i_d + i_D \quad (12)$$

In Equation (12), x_{dsg} denotes the inductive resistance along the d -axis; i_d is the stator current along the d -axis; and i_D is the damping winding current along the d -axis. The stator windings flux linkage along the q -axis, ψ_q , takes the form of Equation (13):

$$\psi_q = x_{qsg}i_q + i_Q \quad (13)$$

where i_Q is the damping winding current along the q -axis; i_q is the stator current along the q -axis; and x_{qsg} denotes the inductive resistance along the q -axis. The field excitation winding current, i_f , can be described as per Equation (14).

$$i_f = \psi_f + \mu_{dsg}x_{dsg}i_d - g_{1sg}i_D \quad (14)$$

In Equation (14), μ_{dsg} is the coefficient of the magnetic flux linkage between the phase windings and the excitation system windings along the d -axis, and g_{1sg} is the magnetic flux linkage coefficient between the excitation and damping windings along the d -axis. The above-mentioned damping winding current along the d -axis, i_D , is shown in Equation (15):

$$i_D = \psi_D + \mu'_{dsg}x_{dsg}i_d - g_{2sg}i_f \quad (15)$$

where μ'_{dsg} is the coefficient of the magnetic flux linkage of the phase windings with damper winding along the d -axis, and g_{2sg} are the magnetic flux linkage coefficients between the excitation and damping windings along the q -axis. The damping winding current along the q -axis, i_Q , can be represented by Equation (16):

$$i_Q = \psi_Q - \mu_{qsg}x_{qsg}i_q \quad (16)$$

In Equation (16), μ_{qsg} is the coefficient of the magnetic flux linkage of the phase windings with damper winding along the q -axis. The mechanical torque, T_{De} , created by the SG is described by Equation (17):

$$T_{De} = \psi_d i_q + \psi_q i_d \quad (17)$$

For the mathematical description of excitation systems, the general IEEE AVR models [29] are commonly used. The differential equations of the AVR model can be written both in matrix and analytical forms, but for practical purposes, the voltage control model can be described using fairly simple nonlinear equations. Thus, the excitation system voltage, U_f , is represented by Equation (18):

$$U_f = i_f - \Delta E, \quad 0 \leq U_f \leq U_{fmax} \quad (18)$$

where i_f is the excitation system current as defined in Equation (14); $U_{f \max}$ denotes the maximum excitation voltage limit; and ΔE_f characterizes the AVR voltage correction value, which takes the form of Equation (19):

$$\frac{d\Delta E_f}{dt} = \frac{K_{avr}}{\tau_{avr}} \left[K_k (U_{ref} - U_{DG}) - \Delta E_f \right], \Delta E_{f \min} \leq \Delta E_f \leq \Delta E_{f \max} \quad (19)$$

In Equation (19), $\Delta E_{f \min}$ and $\Delta E_{f \max}$ are the minimum and maximum AVR voltage correction values, respectively; k_{avr} is the droop coefficient; K_k is the voltage corrector gain coefficient; τ_{avr} is the AVR time constant; and U_{DG} and U_{ref} are the DG's output and reference voltages, respectively.

2.4.3. Model of Energy Storage System

A mathematical description of the ESS's inverter in the d - q system [30,31] can be represented by the differential equations that follow. The output current along the d -axis, i_{dL} , is written as per Equation (20):

$$L \frac{di_{dL}}{dt} = -r_{inv} i_{dL} + \omega_{ESS} L i_{qL} + U_{dc} m_d - U_{dC} \quad (20)$$

where U_{dc} is the DC bus voltage; m_d is the modulation coefficient along the d -axis; U_{dC} is the inverter's output voltage along the d -axis; r_{inv} is the inverter's active resistance; and ω_{ESS} is the output frequency of the inverter. Note that, by defining $\omega_{ESS} = \omega_{DG}(t - \tau_{inv})$, the output frequency is the frequency from the DG model taking into consideration the inverter time constant, τ_{inv} . The output current along the q -axis, i_{qL} , is represented by Equation (21):

$$L \frac{di_{qL}}{dt} = -r_{inv} i_{qL} - \omega_{ESS} L i_{dL} + U_{dc} m_q - U_{qC} \quad (21)$$

In Equation (21), U_{dC} is the inverter's output voltage along the q -axis, and m_q is the modulation coefficient along the q -axis. Equation (22) represents the inverter's output voltage along the d -axis, U_{dC} .

$$C \frac{dU_{dC}}{dt} = \omega_{ESS} C U_{qC} + i_{dL} - i_{dLoad} \quad (22)$$

where i_{dLoad} is the load current along the d -axis. The inverter's output voltage along the q -axis, U_{qC} , is shown in Equation (23).

$$C \frac{dU_{qC}}{dt} = -\omega_{ESS} C U_{dC} + i_{qL} - i_{qLoad} \quad (23)$$

In Equation (23), i_{qLoad} is the load current along the q -axis. The inverter current, i_{inv} , is determined as the root mean square value of the components along the d - and q -axes, as per Equation (24):

$$i_{inv} = \sqrt{i_{dL}^2 + i_{qL}^2} \quad (24)$$

Similarly, the inverter voltage, U_{ESS} , can be represented as per Equation (25):

$$U_{ESS} = \sqrt{U_{dC}^2 + U_{qC}^2} \quad (25)$$

The control strategy of the ESS is designed in two stages: (1) internal current control loops and (2) external voltage control loops [6,31].

2.4.4. Model of the Induction Motor

For the mathematical description of the IM, Park's equations are used [28,32]. In the d - q system and proportional units, the model of the induction motor is described by

differential and algebraic equations (Equations (26)–(36)), which follow below. The flux linkage of the stator winding along the d -axis, $\psi_{d\ im}$, is represented by Equation (26):

$$\frac{d\psi_{d\ im}}{dt} = \omega_{im}(U_d + \psi_{q\ im} - r_{im}i_{d\ im}) \quad (26)$$

where U_d is the voltage along the d -axis; ω_{im} is the frequency; r_{im} is the active resistance; $i_{d\ im}$ is the current along the d -axis; and $\psi_{q\ im}$ is the flux linkage of the stator winding along the q -axis, which can be written as Equation (27):

$$\frac{d\psi_{q\ im}}{dt} = \omega_{im}(U_q + \psi_{d\ im} - r_{im}i_{q\ im}) \quad (27)$$

In Equation (27), U_q and $i_{q\ im}$ are the voltage and current along the q -axis, respectively. The flux linkage of the damper winding along the d -axis, $\psi_{D\ im}$, takes the form shown in Equation (28).

$$\frac{d\psi_{D\ im}}{dt} = \omega_{im}(s_{im}\psi_{Q\ im} - e_{D\ im}) \quad (28)$$

where s_{im} is the IM's slip; $e_{D\ im}$ is the EMF value along the d -axis; and $\psi_{Q\ im}$ is the flux linkage of the damper winding along the q -axis, which can be described by Equation (29).

$$\frac{d\psi_{Q\ im}}{dt} = \omega_{im}(s_{im}\psi_{D\ im} + e_{Q\ im}) \quad (29)$$

In Equation (29), $e_{Q\ im}$ denotes the IM EMF value along the q -axis. The IM slip, s_{im} , is described by Equation (30):

$$\frac{ds_{im}}{dt} = \frac{1}{\tau_{im}}(\psi_{q\ im}i_{d\ im} - \psi_{d\ im}i_{q\ im} + T_m) \quad (30)$$

where τ_{im} is the IM time constant, and T_m is the hydraulic pump mechanical torque. The IM current along the d -axis, $i_{d\ im}$, is shown in Equation (31):

$$i_{d\ im} = \frac{1}{x_{im} - \mu_{im}x_{im}}(\psi_{d\ im} - \psi_{D\ im}) \quad (31)$$

In Equation (31), x_{im} is the inductive resistance, and μ_{im} is the magnetic flux linkage coefficient. The IM current along the q -axis, $i_{q\ im}$, is represented by Equation (32):

$$i_{q\ im} = \frac{1}{x_{im} - \mu_{im}x_{im}}(\psi_{q\ im} - \psi_{Q\ im}) \quad (32)$$

The IM EMF along the d -axis, $e_{D\ im}$, takes the form of Equation (33).

$$e_{D\ im} = \frac{x_{im}}{x_{im} - \mu_{im}x_{im}}\psi_{D\ im} - \frac{\mu_{im}x_{im}}{x_{im} - \mu_{im}x_{im}}\psi_{d\ im} \quad (33)$$

Furthermore, the IM EMF along the q -axis, $e_{Q\ im}$, takes the form of Equation (34).

$$e_{Q\ im} = \frac{x_{im}}{x_{im} - \mu_{im}x_{im}}\psi_{Q\ im} - \frac{\mu_{im}x_{im}}{x_{im} - \mu_{im}x_{im}}\psi_{q\ im} \quad (34)$$

The hydraulic pump braking torque, T_m , can be written as per Equation (34) below:

$$T_m = K_l [m_0 + m_n(1 - s_{im})^2] \quad (35)$$

where K_l is the load coefficient of IM, and m_0 and m_n are the initial and nominal torque values of the driven hydraulic pump, respectively. Finally, the IM braking torque, T_{im} , takes the form of Equation (36):

$$T_{im} = \psi_{q\ im} i_{d\ im} - \psi_{d\ im} i_{q\ im} \quad (36)$$

3. Computer Simulation Results

The computer simulation [21] was carried out based on the SHEPS model described above. The coefficients of the DE, ESG, SG, AVR, and IM were taken in accordance with the manufacturers' technical datasheets [33]. The required coefficients of ESS were taken based on the Siemens Sivacon 8PT converter [34] parameters. The required coefficients of the system under study are shown in Table 2.

Table 2. SHEPS model parameter values.

DE and ESG					
Parameter	Value	Parameter	Value	Parameter	Value
ω_{ref}	0.99 pu	T_{DM}^{max}	1.1 pu	τ_{de}	1.23 s
k_c	0.03 pu	T_{DM}^{min}	−0.25 pu	τ_{esg}	0.2 s
k_{act}	0.012 pu	τ_{se}	10^{-5} s	τ_c	10^{-4} s
SG					
Parameter	Value	Parameter	Value	Parameter	Value
$\tau_{f\ sg}$	2.183 s	r_{sg}	0.011 pu	$\mu_{q\ sg}$	0.895 pu
$\tau_{D\ sg}$	0.893 s	$\mu'_{d\ sg}$	0.929 pu	$g_{1\ sg}$	0.947 pu
$\tau_{Q\ sg}$	0.592 s	$\mu_{d\ sg}$	0.932 pu	$g_{2\ sg}$	0.983 pu
$x_{d\ sg}$	1.94 pu	$x_{q\ sg}$	1.94 pu		
AVR					
Parameter	Value	Parameter	Value	Parameter	Value
U_{ref}	1 pu	τ_{avr}	0.2 s	$\Delta E_{f\ min}$	−1.5
K_k	10	$U_{f\ min}$	0	$\Delta E_{f\ max}$	1.5
k_{avr}	0.03 pu	$U_{f\ max}$	6.5		
ESS					
Parameter	Value	Parameter	Value	Parameter	Value
U_{ac}	1 pu	L_{dc}	0.0942 pu	$\omega_{inv\ ref}$	1 pu
τ_{inv}	0.01 s	r_{inv}	0.015 pu	C_{dc}	0.087 pu
IM					
Parameter	Value	Parameter	Value	Parameter	Value
x_{im}	0.204 pu	μ_{im}	0.944 pu	m_0	0.12 pu
r_{im}	0.046 pu	τ_{im}	0.23 s	m_n	0.79 pu
K_l	0.53 pu				

During the simulation, the developed model elements were set as follows: (a) the coefficients from Table 2 were substituted into the equations of the system under study; (b) the obtained equations were transformed in such a way that the variables on the left sides of the equations had unit values.

The simulation of the SHEPS model under study was carried out using the Simulink application of the MATLAB programming language. The simulation time was set to 10 s. The IM start was set to 5 s into the transient process simulation.

To check the feasibility of the proposed control system, the simulation was carried out with and without the use of the proposed EPC system.

The results of the transient process simulations are shown below. Figures 6 and 7 illustrate the voltage and frequency fluctuations, respectively, of the power system under study caused by the IM direct start without using the proposed EPC system. Based on the simulation results, the voltage drop and frequency deviation are 18.3% and 5.1%, respectively. This will lead to the subsequent activation of undervoltage and underfrequency protection devices [18,35], followed by tripping in both SHEPS power sources and consumers.

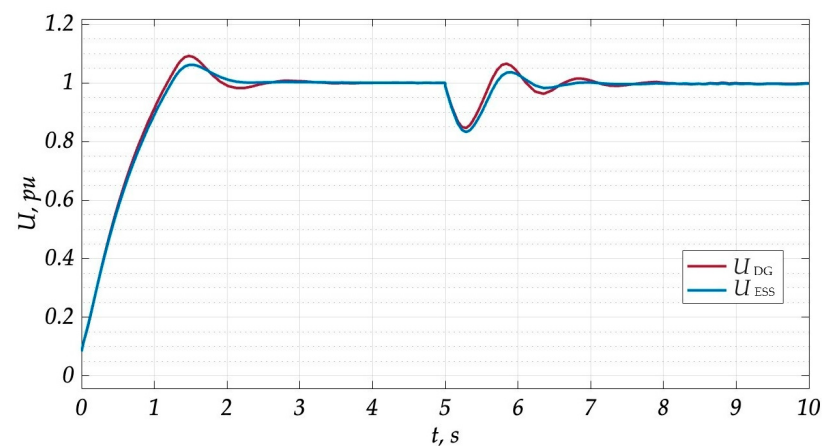


Figure 6. Voltage simulation results obtained without using the proposed EPC system.

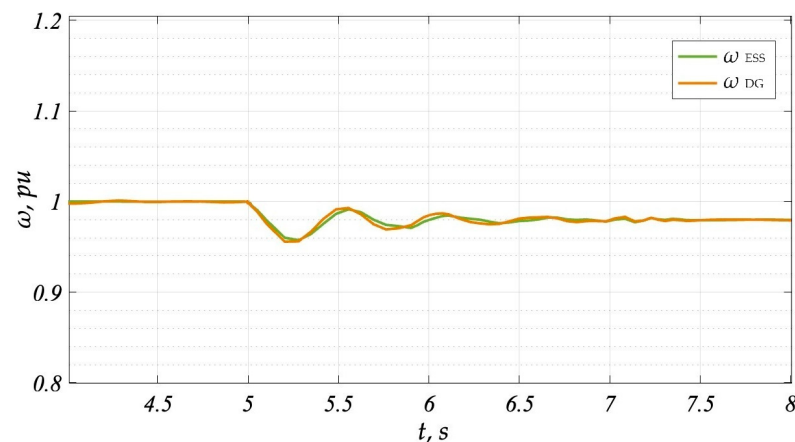


Figure 7. Deviation of DG and ESS frequencies due to direct start of IM obtained without using the proposed EPC system.

Figures 8 and 9 illustrate the voltage drop and frequency deviations, respectively, of the SHEPS power sources under large disturbances caused by the direct start of the IM using the proposed EPC system via a secondary control channel.

While using the proposed EPC system, the maximum voltage deviation is 4.9%, which is within the acceptable voltage deviation range [18]. The maximum deviation of the frequency is 1.8%, which is also acceptable during transient processes [35] under conditions of large disturbances.

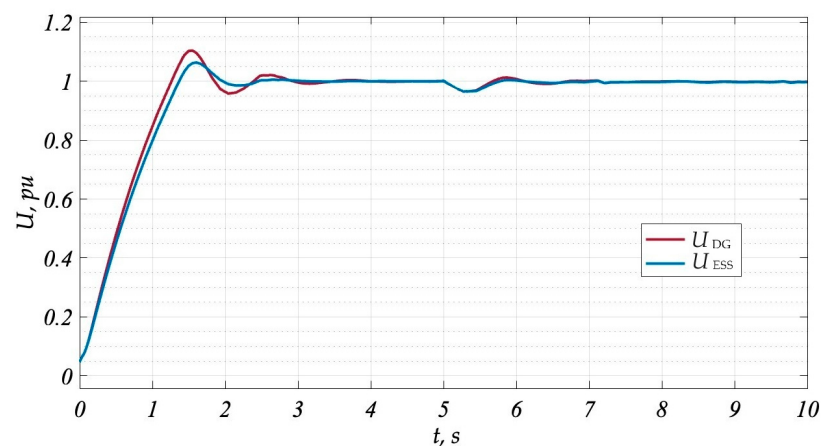


Figure 8. Voltage deviation of SHEPS power sources obtained while using the proposed EPC system.

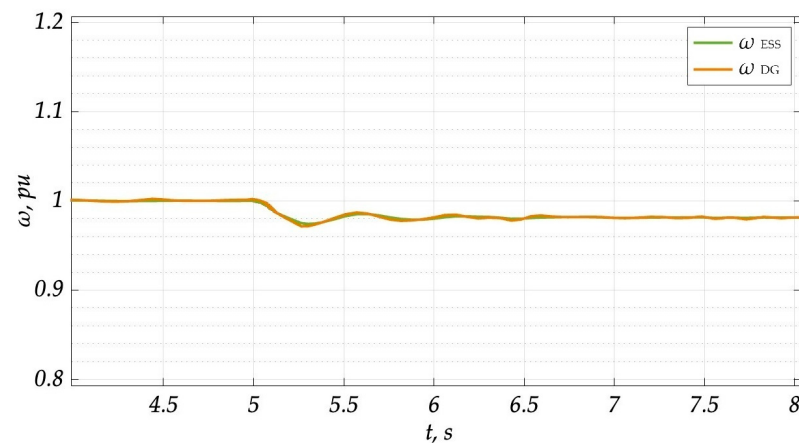


Figure 9. Generated frequency deviations of SHEPS power sources obtained while using the proposed EPC system.

4. Discussion

4.1. Implementation of EPC System

The EPC system can be implemented as an independent control system or a software system integrated into traditional control systems, such as a power management system. The integration of the EPC system via secondary control channels is possible only if local electronic control systems (e.g., ESGs and AVRs) are used. The implementation of the proposed EPC system with mechanical ESGs, as well as analog AVRs, should become a separate research subject.

Secondary EPC is implemented using a cascade control [36], which involves the use of two controllers, with the output of the first controller providing the set point for the second controller, as shown in Figure 10.

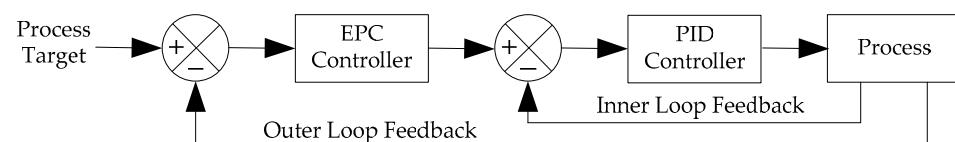


Figure 10. Implementation of the secondary EPC.

The first controller reflects the implementation of the proposed EPC system and control algorithms, while the second controller reflects the operation of traditional control systems based on the PID controller.

While monitoring transient processes, the EPC system compares the controlled parameters' first and second derivative values with the preset threshold. As soon as the threshold is exceeded, the EPC system forms the maximum counteractive control signal for certain executive controls, such as ESG, MC, and AVR, to compensate for the deviation of the controlled parameters in advance. This control signal exceeds and overrides the counterreaction of the traditional control systems while the forecasted values exceed the threshold. On the other hand, this type of counterreaction can cause the opposite controlled parameter deviation; however, this negative effect can be eliminated by adjusting the threshold for forecasted values while going through the simulation process to achieve acceptable deviation values when a controlled parameter is within the acceptable limits. Furthermore, the threshold values of speed and acceleration (first and second derivatives), which characterize the controlled parameters' dynamics and thereby determine the operating mode of the SHEPS, can be found in each particular case using the methods of expert assessment or experimental measurement at the stage of designing and building the SHEPS. At the same time, the problem of false control action as a consequence of EPC system hardware or software failure remains unstudied and would benefit from becoming the focus of future research.

4.2. Limitations

Several limitations that might have had a significant impact on the results in this paper have been determined and will become subjects for further research:

- The inverter model was adopted with the assumption that the battery discharge process is not considered but assumed to be constant, corresponding to the maximum charge level.
- The mathematical models of the monitoring circuits and instrumentation such as frequency and voltage sensors are not considered, assuming them to be ideal sensors without time constants.
- The generated harmonics of voltage and frequency are not considered while assessing the power quality.

5. Conclusions

All SHEPS elements are defined by the inertia of technical processes, characterized by a finite rate of change in controlled parameters and, therefore, a finite time for developing an emergency state and the fault itself. As a result, EPC for SHEPS can be implemented.

Gaining time to prevent an emergency mode and a fault state can be achieved by expanding the range of equipment control system functions by implementing control principles that allow the anticipation and prevention of emergency factors.

This research shows that the electrical power quality improvement goals can be achieved by increasing the control efficiency of the power system generating sources. The feasibility of the proposed control system was proven using a computer simulation, which was carried out after developing a mathematical model of the SHEPS under study. The results of the study conducted here show that the use of the proposed EPC system will improve power quality when the controlled parameters are within acceptable limits. The voltage and frequency fluctuations of the power system's generating sources caused by the IM direct start without using the proposed EPC system are 18.3% and 5.1%, respectively. While using the proposed EPC system, the maximum voltage and frequency deviations are 4.9% and 1.8%, respectively, which are acceptable during transient processes under conditions of large disturbances. Thus, the EPC system should become a fundamentally important protective component in the field of SHEPS control systems, as well as a power management component that can employ management functions such as the direct shut-down and start of power sources and consumers. At the same time, further research is needed, as the problem of false control action as a consequence of EPC system hardware or software faults remains unstudied.

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