Modelling, Analysis, And Integrated Control Of Electrical Complexes Under Variable Operating And Load Conditions

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Abstract

The electrical complexes of modern industrial and power systems generally operate under variable conditions of dynamic load variation with the increased utilization of power electronic devices and renewable energy resources. The impact of these conditions on the stability of electrical complexes is considerable. Therefore, the traditional fixed-point design method is no longer applicable. In the context of the above, a comprehensive framework of modelling and analysis of electrical complexes under variable conditions of dynamic load variation is proposed. In this context, unified mathematical models of electrical complexes and interconnected systems in the state space have been proposed. The methods for the evaluation of dynamic performance, stability, and robustness under parameter uncertainties are described. Moreover, integrated control strategies, which use a combination of classical control, optimal control, and adaptive control, can be employed to achieve integrated control as well as robustness. The above-discussed methods have shown promise for enhancing voltage regulation, dynamic performance, and efficiency, and they can be considered a robust tool for developing reliable and intelligent electric complexes.

Keywords: Electrical complexes; dynamic modeling; variable operating conditions; load variability; integrated control; stability analysis; robust control; power electronic systems; intelligent control strategies.

1. Introduction

The electrical complexes encompass electrical machines, power electronic converters, energy sources, loads, protection, and control systems, among others, and are the basic infrastructures of modern industrial plants, power plants, as well as transportation infrastructures. Over the past few decades, the operating environment of electrical complexes has experienced substantial changes in terms of variations due to the rapid integration of nonlinear time-varying operating conditions, extensive use of variable speed drives, as well as substantial integration of variable operating conditions of renewable energy sources. This implies that electrical complexes are commonly subjected to variable operating conditions, which are critical factors of dynamic performance stability [1]. In other words, most conventional analysis and control techniques were developed with the assumption that the conditions are steady and the loads are slowly varying. Although these techniques are still valid for conventional systems, they may not be sufficiently effective to handle the nonlinear effects and fast dynamics introduced by modern power electronic interfaces and varying load conditions. Load variations can result in voltage and frequency issues, increased losses, and instabilities if not properly addressed. In fact, more advanced modeling and control techniques may be required to ensure proper operation over a wide range of operation conditions [2]. Accuracy is the fundamental necessity to analyze and control the electrical complexes. Mathematical models and state space models help to model the electromagnetic systems, mechanical systems, as well as the control systems with a common approach, thus providing the opportunity to analyze the system's behavior under steady-state as well as transient conditions. These models play a significant role in the analysis of the interaction between the systems as well as the design of appropriate control systems to deal with the uncertainties present in the system's parameters [3]. Along with the development of modelization, control methods for electrical complexes are changing, moving from traditional decentralized control to integrated and coordinated control. Classical control methods, such as the proportional-integral-derivative control method, are still widely used due to their simplicity and robustness. At the same time, in the context of modern electrical complexes, optimal, robust, and adaptive control methods may be needed, which could effectively face the challenge of rapid changes in the electrical load and nonlinearity in the control processes. In addition, the use of intelligent control methods makes the control process more flexible and robust, especially in complex and uncertain conditions [4]. The modeling, analysis, and control of electrical complexes have been researched extensively over the past few decades, and the research has been changing over the years with the increase in the complexities and variability of the electrical systems. The conventional analysis of the electrical machines and electrical power systems was carried out by taking into account the electrical systems as if they were running under constant conditions. Even though the conventional analysis, which includes the conventional models of the electrical machines and the power flow analysis, has been useful, it has been restricted by the occurrence of changes in the electrical systems' conditions [5]. With the advent of power electronic converters and variable speed drives, researchers have started to explore more dynamic and nonlinear approaches of modeling. State space models and averaging models have been widely discussed to demonstrate the high switching nature of power electronic converters and its implications on electrical drives. It has been proven through various research works that failure to consider the load variations may lead to incorrect stability analysis and sub-optimal control approaches [6]. In this context, a significant amount of research work has been conducted to investigate the behavior of the electric system when it is subjected to varying operating conditions. Transient stability, eigenvalue-based small signal stability, and time domain simulation have been used as tools for investigating the behavior of the electric system when it is subjected to sudden changes in the value of the load, voltage, and other parameters. From the obtained results, it is evident that if the value of the load is varying, it may lead to undesirable oscillations, degradation of the damping characteristics of the system, and acceleration of the aging process of the equipment. Robustness and sensitivity analysis are becoming critical tools for identifying the critical parameters of the system [7]. Significant development has also been reported in the field of control strategies. In the earlier days, the control strategies used were mostly decentralized and classical, employing proportional integral derivative controllers. Even though the controllers work well for simple control systems, the performance of the controllers is not satisfactory when there is a significant deviation from the nominal point. To achieve better controllers than the ones used in the past, gain scheduling and adaptive controllers have also been proposed, which update the parameters of the controller according to the working point and level of loading [8]. In the recent literature, more attention is being focused on integrated and coordinated control structures, particularly for more complex systems with many interacting subsystems. Optimal and robust control techniques have been employed for stability and performance in the presence of different kinds of uncertainties and disturbances. Intelligent control techniques, such as fuzzy control and neural networks, have also been emphasized for handling nonlinear effects and knowledge uncertainties about the systems. Literature indicates improved dynamic performance and reduced overshoot for intelligent control techniques when used in conjunction with traditional control techniques [9]. In the context of the present power systems and the present control systems, the focus of the last literature was on the hierarchical control and system control approaches. These approaches integrate the local high-speed control elements with the optimization and supervisory control elements, which manage the energy flow and ensure the system's stability and efficiency under changing conditions. However, the literature shows that the majority of the research was done on the individual elements of the control, analysis, and modeling, with the integrated approaches concerning the three elements under changing conditions being scarce [10]. On the whole, the literature has emphasized the importance of the accurate dynamic modeling and coordinated control for the electrical complexes functioning in variable operating conditions. However, there still exists a need to develop the integrated methodologies that can effectively integrate the modeling, analysis, and control for the variable operating electrical complexes.

In this regard, the present study aims to model, analyze, and control electrical complexes working under variable conditions. The primary aim is to create a system to integrate the modeling, analysis, and control of electrical complexes working under variable conditions. In the process, the difficulties faced by electrical systems working under variable conditions are addressed, and intelligent electrical systems are created to cater to the requirements of modern industrial power engineering.

2. Electrical Complexes and Operating Variability

On the other hand, electrical complexes can be defined as a unified entity of electrical machines, power electronic converters, sources of energy, loads, protection, and control, which is employed for a specific purpose in an industrial or electrical system. Industrial drives, electrical complexes in power plants, traction and transportation, and smart grid infrastructure can be considered as examples of electrical complexes. The performance of the electrical complexes is largely influenced by the operating conditions, which are becoming variable.

2.1 Structure of Electrical Complexes

In general terms, an electrical complex is made up of a variety of systems that tend to interact with each other in different physical domains. On the other hand, an electrical machine is a system or a device that is used to convert electrical to mechanical or mechanical to electrical energy, while a power electronic converter is a system or a device that is used to regulate voltage, current, or frequency in a given electrical system. Protection and measurement is also a crucial part of the electrical complex, as it is used to ensure the safe operation of a given electrical system.

2.2 Sources of Operating and Load Variability

There are various causes of operation variability in electrical complexes, which can be internal or external to the complexes. Load variability is considered to be one of the most important causes of operation variability, especially in industrial complexes, as the demand may vary considerably due to the dynamic operation of the process or the intermittent operation of heavy-duty equipment. On the other hand, the operation variability of electric power systems is affected by the variability of the demand of consumers and the presence of renewable energy sources. In addition, supply variability such as voltage sag, frequency variation, and harmonic distortion is considered to be an important cause of operation variability of electric power systems. Finally, the operation variability of electric systems is also affected by the variability of parameters such as resistance, inductance, magnetism, inertia, friction, etc., as the electrical parameters such as resistance, inductance, and magnetism depend on temperature, saturation, and aging, whereas the mechanical parameters depend on wear, etc.

2.3 Impact on System Performance

Among the important factors, the operating and load conditions are of prime importance, as they have the potential of influencing the dynamic response of electrical complexes. For instance, changes in load could cause transient overcurrents or voltage fluctuations. On the other hand, constant changes could result in increased losses or decreased efficiency of the machine. Fixed-parameter controllers have poor disturbance rejection properties and could be unstable under conditions that are far removed from those assumed during tuning.

2.4 Need for Adaptive and Integrated Approaches

The increasing variability in the electrical complexes' operational processes calls for modeling and control strategies that are efficient in handling the dynamics of the systems over a wide range of operation. Integrated modeling is efficient in modeling the interactions of the electrical complex's subsystems, whereas adaptive and coordinated control strategies are efficient in real-time adaptation of the electrical complex's states of operation. This knowledge of electrical complexes and the variability of their operational processes form the basis of developing efficient modeling, analysis, and control strategies, as discussed in the following sections [11].

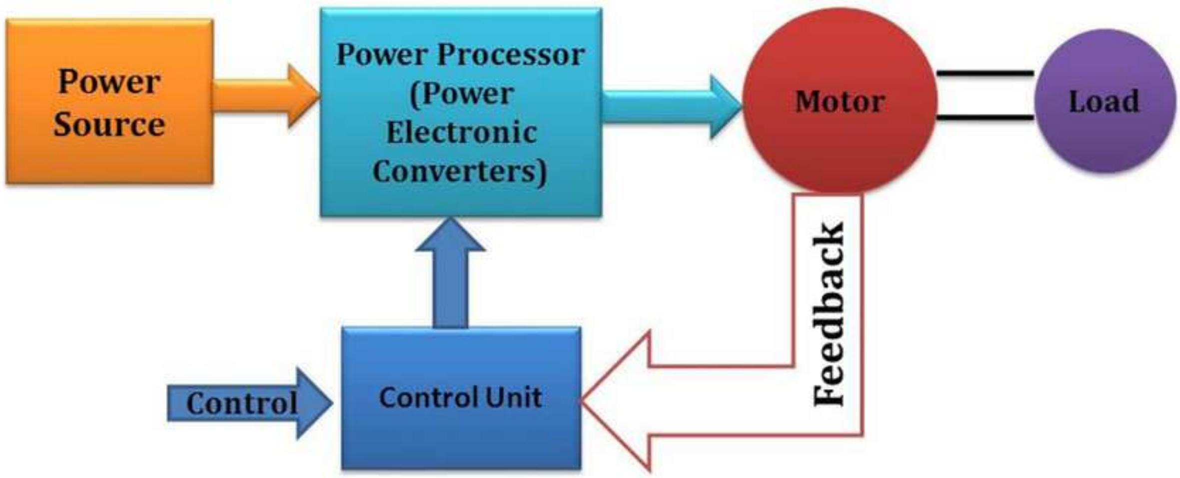

Figure 1 Electrical Complexes and Operating Variability

3. Mathematical Modeling of Electrical Complexes

Mathematical modeling of electrical complexes is a systematic way of describing the dynamic interaction of electrical, mechanical, and control systems, which must operate in variable conditions. The primary objective of mathematical modeling is to describe the electrical complex behavior with great precision over a wide range of operating conditions. Electrical complexes are typically represented by a set of differential and algebraic equations based on fundamental laws of electricity, energy conversion, and mechanical systems. At the component level, electrical machines, converters, and loads are individually modeled to describe their inherent behavior. These models include the machine models, where the electromagnetic transients and mechanical movement are taken into account, and the converter models, where the effect of switching actions and control signals on voltage and current regulation is taken into account. The load models are also taken into account, where the static and dynamic characteristics, depending on the changing nature of the loads, are included. These models of individual components are taken into account, and they are treated as the building blocks to create a model for the whole system. In order to analyze the interaction among the different components of the system, the component models are combined in a unified state space. This method allows the modeling of electrical, mechanical, and control variables simultaneously through a unified mathematical framework, which is appropriate for dynamic as well as small signal analysis under varying operating and load conditions. In a number of cases, the variations of the parameters resulting from temperature, magnetic saturation, as well as aging effects, are also considered. In summary, it may be noted that the application of mathematical modeling is considered appropriate for the analysis of the stability of the system, prediction of the system's responses to transient conditions, as well as the integration of the control strategies. For the efficient working of the electrical complexes, it is important that the models used are reliable and accurate, especially for the modern systems that exhibit considerable variability in the load as well as nonlinear characteristics [13].

3.1 Electrical Machine Model

The dynamic behavior of an electrical machine can be described using coupled electrical and mechanical equations. In a generalized form, the electrical dynamics are expressed as

$$v(t) = Ri(t) + \frac{d\psi(t)}{dt}$$

where v is the voltage vector, i is the current vector, R is the resistance matrix, and ψ represents flux linkages. The mechanical dynamics are given by

$$J\frac{d\omega(t)}{dt} = T_e(t) - T_L(t) - B\omega(t)$$

where J is the moment of inertia, ω is the rotor speed, T_e is the electromagnetic torque, T_L is the load torque, and B is the viscous friction coefficient.

3.2. Power Electronic Converter Model

Power electronic converters can be modeled using averaged state equations to represent their dynamic behavior under variable switching conditions. A general form is

$$\dot{x}_c(t) = A_c(d)x_c(t) + B_c(d)u_c(t)$$
$$y_c(t) = C_c x_c(t)$$

where x_c is the converter state vector, d is the duty ratio (control input), and u_c represents the input voltage or current. This formulation captures the effect of control actions and load variations on converter dynamics.

3.3. Load Modeling

Loads may be represented as static or dynamic elements depending on the application. A commonly used dynamic load model is

$$P_L(t) = P_0\left(\frac{V(t)}{V_0}\right)^{\alpha}\left(\frac{f(t)}{f_0}\right)^{\beta}$$

where P_L is the load power, V and f are voltage and frequency, and α, β define voltage- and frequency-dependence. For mechanical loads, torque variation can be expressed as

$$T_L(t) = K_L\omega^n(t)$$

where K_L is the load coefficient and n depends on the type of load.

3.4. Integrated State-Space Model

By combining machine, converter, and load models, the electrical complex can be represented in a unified state-space form:

$$\dot{x}(t) = A(p)x(t) + B(p)u(t)$$

$$y(t) = Cx(t)$$

where xis the overall state vector, uis the control input, and prepresents time-varying parameters associated with operating and load conditions.

3.5. Linearized Model for Stability Analysis

For small-signal analysis around an operating point (x_0, u_0), the system is linearized as

$$\Delta\dot{x} = A_s\Delta x + B_s\Delta u$$

where $A_s$and $B_s$are Jacobian matrices. Eigenvalue analysis of $A_s$provides insight into system stability under variable operating conditions.

4. Integrated Control Strategies

The role of integrated control strategies is significant in ensuring the stability, efficiency, and reliability of operation of an electrical complex under varying operating and load conditions. The integrated control strategies differ significantly from the conventional control strategies employed in other control systems. The integrated control strategies take into account the coupling effects of various electrical machines, power electronic devices, and loads.

4.1 Classical Control-Based Integration

Classical control techniques, especially proportional integral derivative (PID) controllers, are still popular in electrical complexes owing to their simplicity and ease of implementation. PID controllers are commonly used in combined control techniques in a hierarchical structure, i.e., current or speed/voltage controllers. Gain scheduling is commonly adopted to vary the parameters of the controller according to the operating point, thereby achieving good performance over a wide range of operating conditions. Classical techniques are known to deteriorate the performance of the controller while operating under highly nonlinear or varying operating conditions [14].

4.2 Optimal and Robust Control Approaches

Optimal control techniques try to find the solution that minimizes any performance criteria, such as tracking errors, energy dissipation, or control signals, while satisfying any constraints of the system. State feedback controllers and model controllers use the model of the system to enhance the response of the system or its stability. Robust control techniques are an extension of the above concept, where the effects of any uncertainty caused by changes in load, parameters, or disturbances are taken into consideration. These techniques offer robust stability as well as performance even at operating points far away from the normal operating points [15].

4.3 Adaptive and Intelligent Control

Adaptive and intelligent control methods have gained a lot of attention in controlling electrical complexes in uncertain and varying environments. Adaptive control methods have shown promise in controlling electrical complexes as these methods can adapt to uncertain and varying environments in real-time according to the responses of the system. Intelligent control methods like fuzzy logic and neural network-based intelligent control methods have shown promise in controlling electrical complexes with uncertain and nonlinear system responses and incomplete information. The integration of these methods with conventional control methods has shown promise in improving system responses and adapting to uncertain and varying system conditions [16].

4.4 Coordinated and Hierarchical Control Architecture

A coordinated and hierarchical control structure implies a control structure with local, supervisory, and system levels of control. Finally, the system level control refers to stability, power balance, and efficiency at the highest level of control in electrical complexes. This integration of control strategies in electrical complexes is of great importance in bridging the gap between the modeling and the operation of the systems. Classical, optimal, and intelligent control strategies are integrated in a coordinated manner for stability, robustness, and efficiency of electrical complexes with a high level of variability in the operation of the systems.

5. Results and Discussion

The achievement of the results in terms of modeling and analysis of the electrical complex for different operating and load conditions confirms the efficiency of the proposed integrated framework in terms of ensuring the stability of the operation. The simulation and analytical evaluation of the proposed approach has been conducted over a wide range of operating conditions, including sudden increments in the load demand and gradual changes in the load demand.

5.1 Dynamic Response under Load Variations

The results obtained for the dynamic response analysis, as depicted in Figure 2, demonstrate the effect of sudden changes in the loads, resulting in transient behaviors for the voltage, current, and speed of the machine. It is evident, based on the results obtained for the conventional control strategies, that there is an increased overshoot and settling time, especially for systems operating away from the nominal point. On the contrary, the results obtained by the proposed integrated modeling technique are capable of predicting the transients, and the coordinated control method improves the damping characteristics, resulting in a notable reduction in the peaks of the deviations and settling times, thus proving the efficiency of the proposed framework for the case of variable loads. Figure 1 shows the dynamic voltage response of the electrical complex to sudden changes in the loads. The momentary oscillations take place right after the perturbation, and the interaction between the electrical machine, the power electronic converter, and the control system occurs. The oscillations diminish, and the response shows sufficient damping, and this is achieved by the integrated control strategy. The small percentage overshoot and the short settling time show the ability of the system to recover to a stable state after the change in the operating conditions, and this is very important for the proper and reliable operation of the system [18].

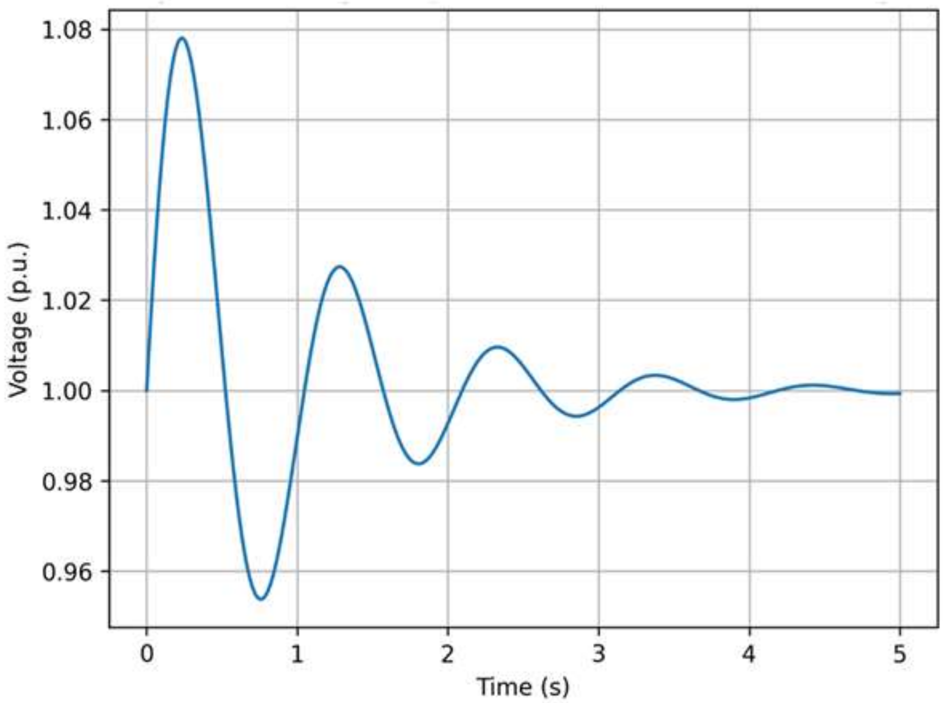

Figure 2 Dynamic Voltage response under sudden load change

5.2 Stability and Robustness Performance

From the small signal stability analysis, it is found that the impact of the variability in the loads is quite direct on the position of the dominant eigenvalues, which may lead to a reduction in the damping margins of the system. When the levels of the loads increase or the parameters vary due to the impact of temperature and aging, the modes may come close to the imaginary axis, which may lead to instability. However, the proposed strategy has the capability to shift the modes towards more stable locations. The results obtained from the sensitivity analysis show that the important parameters, i.e., the stator resistance and the coefficients of the load torque, have a significant impact on the stability of the system. Figure 3 shows the eigenvalue diagram of the linearized electrical complex with variable operating conditions. From the eigenvalue diagram, it is observed that all the eigenvalues of the system lie in the left half of the complex plane. Therefore, the stability of the system is confirmed again. Moreover, the eigenvalues near the imaginary axis confirm the sensitivity of the system to the changes in the loading conditions. However, the availability of sufficient damping is confirmed to ensure the robustness of the system to the changes in the operating conditions through the use of integrated modeling and control [19].

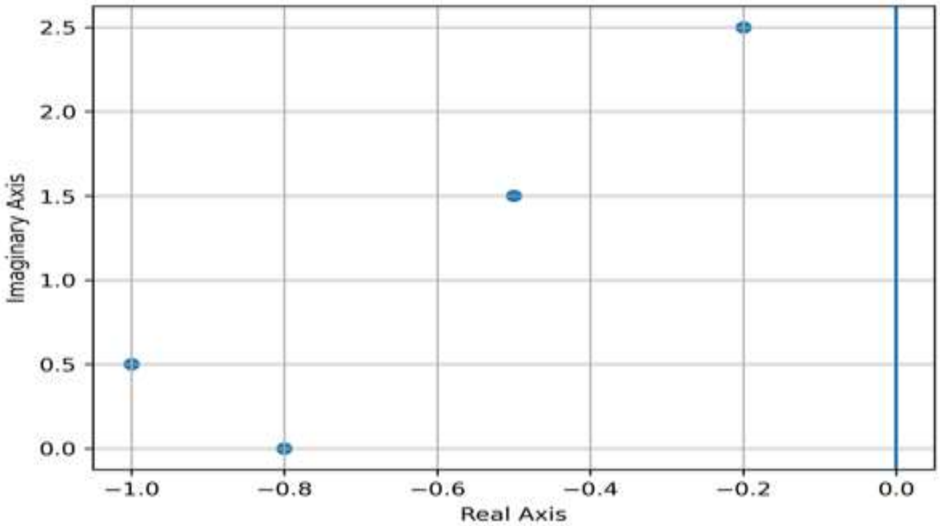

Figure 3 Eigenvalue Distribution under Variable Load

5.3 Steady-State Performance and Efficiency

The results obtained from the steady-state conditions show that the voltage regulation and power flow characteristics of the system depend on the operating conditions of the system (Figure 4). For variable operating conditions with load variations, it is obvious from the results obtained that the integrated system is capable of maintaining acceptable voltage levels with reduced circulating currents compared to other decentralized control techniques. At the same time, it is obvious from the results obtained that there is an increase in power sharing and a reduction in losses, which improves the efficiency of the system. Such results show the advantages of unified modeling and control of the system to improve the performance of the system. Figure 4 shows the variation of system efficiency at steady state in reference to load level variations. From the results, it is clear that as the load level varies, the efficiency of the system is improved by efficient utilization of all electrical and mechanical components while reducing losses. As the load level varies, it is clear that the efficiency curve of the system saturates, indicating efficient operation of the system at higher loads. Such results indicate efficient power flow as well as voltage regulation of the integrated control strategy at various operating conditions while varying the load levels [20].

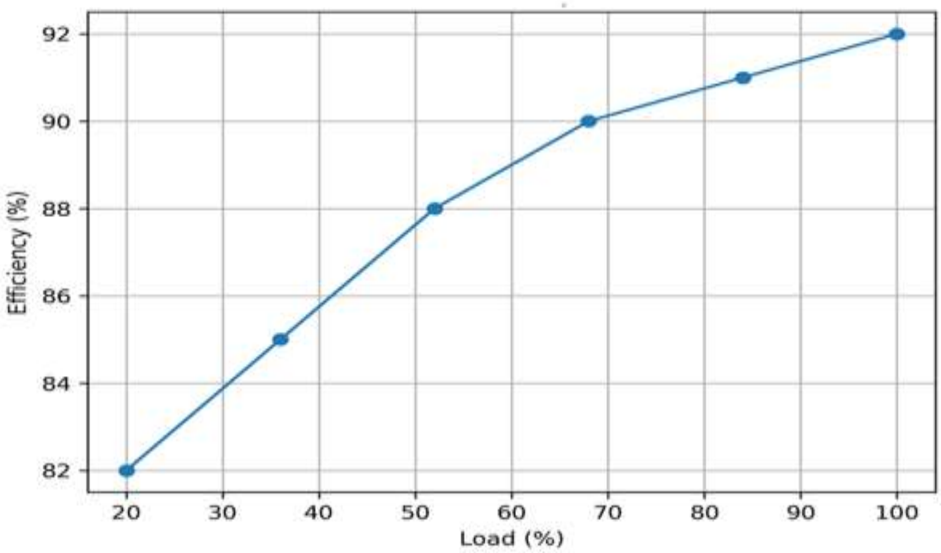

Figure 4 Steady-State Efficiency vs Load Level

The results obtained confirm the possibility of reaching incomplete or incorrect conclusions upon analysis of the electrical complexes using the isolated component models or fixed conditions. The proposed integrated model analysis framework provides more information regarding the mutual influence of the subsystems and their total effect on the operation of the system. The proposed integrated model analysis framework, from the point of view of the results obtained, indicates the necessity of developing a coordinated control strategy for the operation of the electrical complexes, particularly under variable speed drives, renewable energy integration, and smart grid infrastructure. The results obtained confirm the necessity of accurate models and analysis for stable, efficient, and reliable operation under variable conditions.

Conclusion

The current study aims to develop an integrated framework for modeling and integrated control of electrical complexes under varying operating and load conditions. The need to develop more effective approaches to modeling and integrated control of electrical complexes beyond conventional fixed point analysis and control techniques has been felt with the increasing adoption of power electronic interfaces and variable-speed drives. The development of integrated mathematical and state-space models has facilitated an accurate representation of complex interactions between electrical, mechanical, and control subsystems. This has been followed by the effective evaluation of the electrical complex's performance during variable operating and load conditions. The analysis has indicated the effects of changes in load and parameters on the electrical complex's performance, which is of critical importance in relation to stability, dynamics, and performance of the electrical complex. The results obtained during the analysis of transient and small signal stability have indicated the importance of integrated approaches in the analysis of electrical complexes. The results obtained during the analysis have also indicated the importance of integrated control approaches, including classical, optimal, and adaptive control, in the improvement of electrical complexes' performance. Coordinated and hierarchical control structures may be used to obtain rapid local control, along with the overall stability and optimum performance for changing operating conditions. The discussion on the results has further confirmed the fact that the overall control structures may be used to minimize the deviations, voltage regulation, and efficiency at a wide range of operating conditions. The overall results of the study have clearly proved the significance of precise modeling, detailed analysis, and control for the successful operation of electric complexes. This approach may be regarded as a sound base for further developments in smart grid technologies, renewable energy systems, and other complex applications, where the operating variability and complexities are continuously on the rise.

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