Discrete Event Systems modelling and control in Smart Grids: A survey of recent advances

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Abstract: Discrete event systems theory has effectively been applied to different of power systems operation and control ranging from generation, transmission and distribution to communication systems. Various scenarios come into play as renewable energy sources, energy storage facilities, electric vehicles etc. are getting connected to the grid. Electric grid is becoming smarter with addition of smart meters and devices. Increased amount of sensor data and data analytics gather a good amount of valuable information. Smart grid concept is getting accepted worldwide. A high level analysis based on discrete event system modelling can significantly improve flexibility and modularity of the Smart Grids. Historically there have been several works to implement discrete event modelling based operation and control of power system components or of the whole system. This paper presents a survey of recent works related to application of discrete event methods relevant to smart grids.

***Index Terms*- Discrete event systems, smart grid, power system operation and control, fault diagnosis.**

I. INTRODUCTION:

Dynamic systems can be classified into continuous-time systems and Discrete Event Systems (DES). The former represent ‘‘physical’’ system behaviour, typically using differential equation models, while the latter deals with the logical and sequential behaviour of systems using discrete state and event driven models[1]. Power system involves components having both kinds of dynamics. Potential for DES application in smart grid is immense as evident by the literature. A typical hybrid system which comprises of continuous processes and discrete events is illustrated in [13].The objective of this system is to prevent under-frequency generator failures by making small and rapid changes to the network load. The idea is to allow small service interruptions when under-frequency failures are imminent, and then to automatically restore service when the system stabilizes. Figure 1 shows the scheme.

Technological advances are now enabling reduction in renewable and non-conventional energy production costs. Environmental concerns force increased use of such non-conventional sources of energy. Due to their modularity and simple erection requirements, these generation methods are now increasingly being embraced by even common households. Smart grids which utilize digital communications channel to effectively analyze and control electrical power networks, now have to accommodate such distributed generation units as well. With the advancements in battery technology and other energy storage technologies energy storage infrastructures are also coming up which may make the highly stochastic renewable energy to be stored and supplied at will. New loads like electric vehicles are getting connected to the grid. There is also now a growing trend in integration of sensors and sensor based systems with cyber physical systems and device-to-device (D2D) communications [2]. 5th generation wireless systems (5G) are coming up and Internet of Things (IoT) is gaining prominence as devices are expected to form a major portion of this 5G network paradigm. Smart grids will increasingly include 5G devices. As more such components are included which may be influenced by several factors like weather and demand, frequent inclusion and removal of such systems from grid necessitate the analysis and control of the grid connected systems on the basis of occurrence of events.

1.1 Applications of DES modelling and control in Smart Grids:

With regard to the notion of DES modelling of Smart Grids, the area of research can be classified into two parts: i) one that deals with normal operation and control of the power system and communication network and, the one that deals ii) fault diagnosis of power systems.

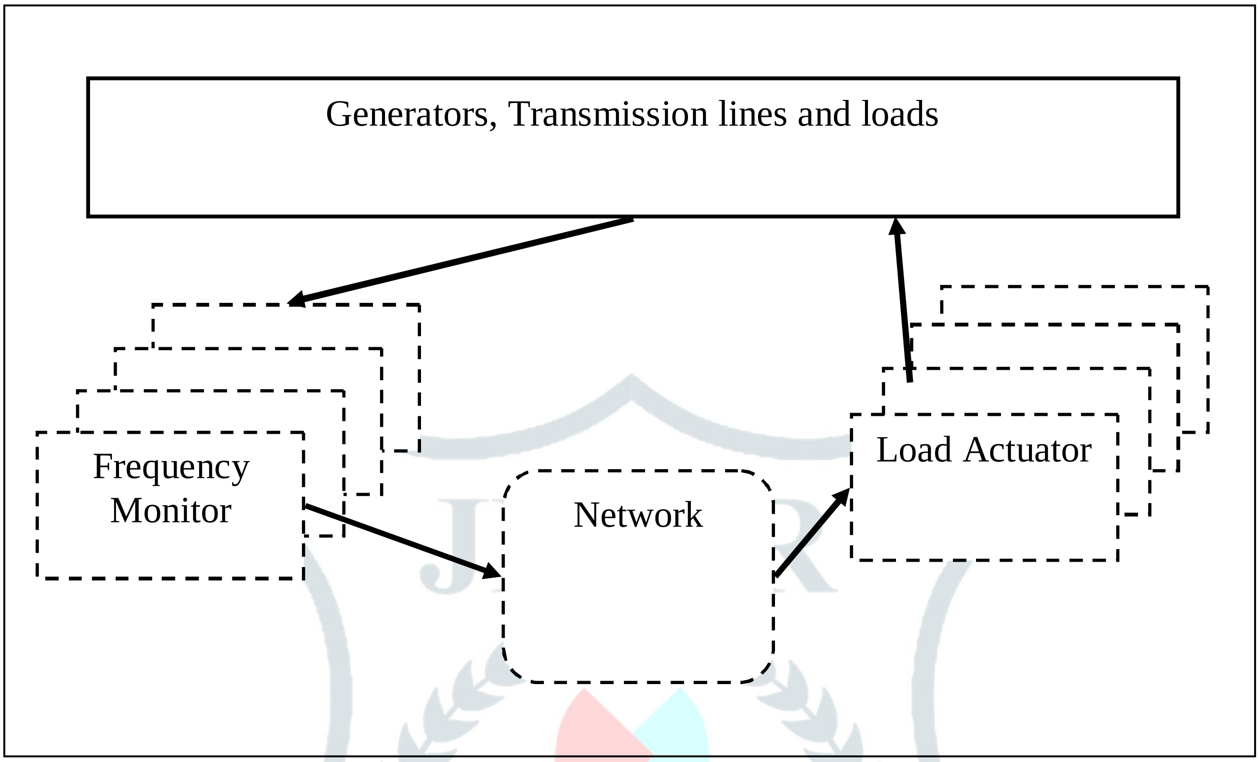

Figure 1: Components and their interconnections in the power system model. A solid outline indicates

1.1.1 DES modelling of power system operation and control:

In [3] the requirements and a concept for a modular Smart Grid simulation framework based on an automatic amalgamation of existing, heterogeneous simulation models are presented. The composition problem is broken down into different layers, for each of which first concepts for solving the problem are presented. A prototype showing the feasibility of the presented concept has been developed. Simulation results of a Smart Grid scenario including electric vehicles as well as renewable energy sources are presented. Limitations and possible improvements are also discussed.

Most of the supervisory control techniques focus on (passively) maintaining system safety and health by the means of disabling some controllable events. It has neglected the possibility of actively enforcing certain events that is widely practiced in the control of real world DES applications. Event enforcement can be quite useful in both “driving” the system toward the given objective (e.g., marked states) and actively maintaining system safety. This paper addresses this issue. Finite state machines are used in supervisory control. To mitigate the problem of state explosion which is often encountered with finite state machines, in [4] Junhui Zhao et al. propose a method that employs both finite state machines and sets of variables in modelling discrete event systems.

In [1] has shown that many control actions needed in Power System can be analyzed with DES approach. Various control requirements like Bus voltage control, Security Control, and Emergency Control are analyzed and possible actions based on discrete event analysis of various conditions are suggested.

In [5], a hybrid system modelling of power systems with continuous or discrete states, continuous dynamics, discrete events or triggers and evolution of states with events is described. The hybrid systems approach helps in the stability and control of power systems.

In [6,7] under-load tap-changing transformers (ULTC) which obviously have discrete-event behaviour are widely employed in transmission systems to take care of instantaneous variations in the load conditions in substations are studied. ULTC may be controlled either automatically or manually. Afzalian et al[6] discusses creation of supervisory controller of ULTC as a discrete-event system. Different components of the ULTC as well as its specified control logic have been modelled as DES. Supervisory controllers are designed for the tap-changer in Automatic and Auto/Manual modes of operation. It is shown that the specifications are controllable and the closed loop control system is non-blocking.

In [8] , an event-triggered control algorithm is proposed for the Load Frequency Control (LFC) scheme of multi area power systems. Main features of the proposed are: 1) the LFC scheme under consideration is comprehensive, which comprises time delays and uncertainties that can reflect more realistic dynamical behaviours; 2) an event-triggered control algorithm is proposed for the LFC scheme of multi-area power systems; 3) the conditions for the system stability under the event-triggered LFC are derived by the free-weighting matrix approach, which is known as the least conservative method.

In [9], authors propose a novel emergency control scheme capable of predicting and preventing a voltage collapse in a power system that is modelled as a hybrid system by considering nonlinear dynamics, discrete events and discrete manipulated variables. Modern power systems are operated close to their stability on account of economic considerations. The modelling and control adopted in this paper helps to deal with such situations effectively.

In [10] analysis of a complex Smart Grid control scheme uses simulation to model both the communication network and the power system. The control scheme uses a wireless communication network to activate distributed storage units in a segment of the electrical grid to compensate for temporary loss of power from a solar photovoltaic (PV) array. The model of the communication network provides a means to examine the effect of communication failures as a function of the radio frequency (RF) transmission power level. An open source event-driven simulator, is used to determine the impact on the electrical power system.

The work by W Sahid et al[11]deals with the admission control of thermal appliances in smart buildings. The scheduling of thermal devices operation is formulated in the framework of discrete-event systems, which permits the modelling and design of admission control to be carried out in an efficient manner and ensuring the existence of the feasible scheduling prior to exploring control solutions. Two algorithms are developed for the purpose of peak demand reduction. While the first algorithm validates the schedulability for the control of thermal appliances, the second algorithm may achieve a more efficient use of available capacity by exploring the concept of max-min fairness. Simulation studies are carried out in MATLAB/Simulink platform and the results show a noticeable improvement on peak power reduction.

A discrete event simulation of electrical networks based on OMNeT++ Discrete Event Simulator is given in [12]. As illustrated in[12] smart grid implementation calls for more co-ordinated functioning considering control, communication and electro-mechanical dynamics. Hybrid systems approach has been used to effectively analyze the power system behaviour. ORNL simulator based simulation of power system is given. In [13] a discrete event approach to electrical load control is given. A system for under-frequency protection of wide area electric power systems given in [13] illustrates several aspects of Type 3 hybrid systems described in the paper. The objective of this system is to prevent under-frequency generator failures by making small and rapid changes to the network load. The idea is to incur small service interruptions when under-frequency failures are imminent, and then to automatically restore service when the system stabilizes.

In The proportion of renewable energy sources in energy production is growing day by day. Domestic homes can be equipped with solar panels, micro combined heat and power systems, batteries, and they can qualify as adaptive consumers. This implies that such consumers can also deliver energy to the grid and react to the energy supply. In [14] a hybrid simulation approach for the analysis of a grid of domestic homes equipped with different technological options with respect to efficiency and costs is presented. For energy storage and energy flows the system dynamics modelling paradigm is used whereas control decisions are modelled as state charts. The highly intermittent solar irradiation and also the electric power and heat demands are implemented as stochastic models. The component-based design allows for quick creation of new case studies. As examples, different homes with batteries, micro combined heat and power systems, or energy carrier carbazole as energy storage are analyzed. A hybrid simulation model is used. System dynamic (SD) models are used to represent continuous processes like energy flow. Control decisions and condition changes such as weather and load are represented by discrete event models. The simulation software AnyLogic (XJ Technologies Company Ltd. 2012) which allows to combine SD and discrete–event modeling in one framework, is used. Components are active objects with internal SD and discrete event parts and can be dynamically connected at run-time, leading to a "dynamic system dynamics" approach, which provides flexibility in connecting arrays of components without the need of manual replication of the SD elements of the system, as would normally be the case.

This [15] paper proposes, for urban areas, a building integrated photovoltaic (BIPV) primarily for self-feeding of buildings equipped with PV array and storage. With an aim of elimination of several energy conversions, a DC network distribution is considered. The BIPV can supply a tertiary building at the same time as PV array may produce power through a hierarchical supervision which is able to exchange messages with the smart grid and metadata. The hierarchical control is intended as an interface to expand the system ability for advanced energy management control having regard to the grid availability and user's commands. It consists of four layers: human-machine interface, forecast, cost management, and operation. The operation layer, implemented in atrial platform, takes into account the grid supply power limits and constrains the DC load. The experimental results endorse the approach that may be a solution for the future smart grid communication between BIPV and utility grid.

In [16] a co-simulation framework, which pools power system simulation and communication network simulation together is proposed. The continuous time model used in power system simulation and the discrete event-driven model used in communication network simulation are studied. Similar simulators for the same purpose can be shown to have coarser grain synchronization induced inaccuracies. An errorless implicit synchronization mechanism for the co-simulation framework is proposed in this work [16]. This co-simulation framework is realized by integrating PSLF and NS2 software. An agent-based supervisory remote backup relay protection scheme is also inspected.

In[17], a state variable modelling method is presented to develop a hybrid large-scale system model of the micro grid. State variable models of individual converters linearized at different operating points are the basis of the model. A large-scale interconnected system model is developed for each feasible interconnection of the linearized models of the converters. The switching model, which is a combination of state based and input based switching events between the large- scale system models, is developed using hybrid system theory. The modelling approach is applied to two example systems consisting of DC-DC converters and a DC bus. The hybrid large scale system models are compared with circuit simulations to show the validity of the modelling process.

1.1.2 Fault Diagnosis

The FAULT diagnosis of Electric Power System (EPS) is a process of isolating faulted system elements by tripping of protective relays and circuit breakers. Various methods, such as ANN, GAs, Tabu, expert system and logic reasoning, etc. can be found in literature, which have been applied to fault diagnosis of EPS. Their purposes are focused to diagnose faults timely on-line so as to provide an accurate judging rule for dispatch operators. Specially, as soon as some serious faults occur in a power system, a lot of information is transmitted to the control centre. Under such situation, the operators are required to judge the cause, location and system elements with faults rapidly and accurately. Thus good fault diagnosis methods can provide accurate and effective diagnostic information to control room operators and ensure safe and satisfactory operation of power system. A general fault diagnosis configuration is illustrated in Fig 2.

Fault Diagnosis of power systems modelled as discrete-event systems is an important area of research.

Often, in the presence of uncertain and in complete information, fault diagnosis in power systems becomes difficult. Use of fuzzy logic and hybrid system modelling in uncertain conditions greatly improves decision making process.

Authors in [18] propose a combination of Petri nets and fuzzy logic for fault diagnosis. The feature of this model is that the initial tokens of Fuzzy Petri Nets (FPN) may be set according to the data of truth value given by users, but the diagnosing process is finally done by the fuzzy reasoning mechanism based on certainty factors and concurrent calculation mechanism of Petri nets.

[19]The work by Baroni et al have presented a model-based technique for the diagnosis of large-scale active power systems, which are distributed discrete-event systems. The discrete events happen asynchronously. The core part of the proposed technique is the reconstruction of the system behaviour based on the system observation. The main problem which has been tackled is the possibly huge size of the search space. Existing discrete event systems diagnosis methods though making far more limiting assumptions (such as permanent faults, synchronous evolution, no unobservable behavioural cycles, or regular architecture) fail to meet the requirements of modularity, incrementality, and parallelism, as they first create (and save) a complete search space, to be visited afterwards. In fact, the generation of complete search space is appreciable since it can help solve every diagnostic problem instance. However generation of complete search space is not practical. Unlike the prevalent methods, the approach presented in[19] incrementally reconstructs the overall behaviour of the system starting from partial behaviours relevant to subsystems.

Protection system failures are recognized as contributing to cascading outages in power system. With the power system becoming more and more complex, fault diagnosis using conventional approaches become less useful. In [20] power system failure diagnosis is done using the discrete event system approach. With the advent of sensor networks and monitoring systems, outputs related to each event can easily be monitored. A modified DES modelling framework using the event based outputs is developed for power system failure diagnosis. A diagnoser is developed using this model for failure diagnosis. Robust diagnosis is considered and minimal bases diagnosers are identified.

In[21] use of Petri nets in power system fault diagnosis is illustrated. This method can be applied for a fast and accurate detection of the various faults associated with the operation of circuit breakers and protective relays in any large power transmission network. It can also serve as a post emergency analysis tool helping the system operators trace back the various causes behind a system failure.

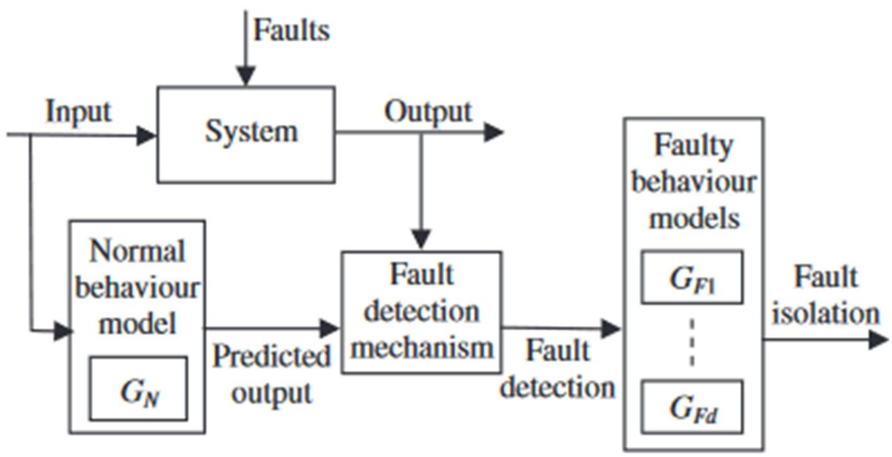

Figure 2: Fault diagnosis configuration as illustrated in [23]

Windfarms are a major source of renewable energy. Stochastic variation in wind velocities and direction. As a result, the unpredictable loading conditions of the wind turbines make it hard to predict degradation and failures. A Discrete Event system modelling approach presented in [22] solves this problem to a significant extent. This helps in the prediction of possible wind farm failures/faults and carry out condition based maintenance.

Fault diagnosis of DES is an active scientific area [23] that has been recently strengthened with many well-recognized formal methods and models. Recent advancements have greatly improved efficiency fault diagnosis process of DESs. These advancements have been accompanied with many adaptations of the concept of diagnosability and associated algorithms to build diagnosers and verify diagnosability. Thus a solid foundation for applying fault diagnosis methods to DES/hybrid models of power system is realized in [23]

II. CONCLUSIONS:

The literature survey has shown that the discrete event systems modelling and control of smart grid is an important area of research as new internet enabled and sensor data based devices and systems are getting integrated into the grid. Renewable energy generation units and unconventional loads like electric vehicle are interacting with smart grids increasingly. Developments in energy storage and AC/DC conversion technologies have transformed the nature of the grid. Weather models can be used to predict the generation and consumption patterns associated with a grid. All these developments necessitate event driven actions in smart grids. It has been seen in the literature that, two main streams of research works viz. the modelling and control of power systems and fault diagnosis of power systems with applications to protection, have become prevalent with regard to discrete event system modelling and control of power systems in general and smart grids in particular.

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