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New Hybrid Petri Net Application for Modeling and Analyzing Complex Smart Microgrid System

Abdul Halim
Department of Electrical Engineering, Faculty of Engineering,
University of Indonesia (UI), Kampus Baru, 16424 Depok, Jawa Barat, Indonesia

Abstract: Smart microgrid has become a promising solution for efficient use of renewable energy resources and enhancing reliability. However, as the number of the system components grows, smart microgrid becomes complex and difficult to analyze. In this study, new Hybrid Petri Net (PN) application is proposed for modelling and analyzing smart microgrid. The model presented is derived from the principle of power balance in a bus. The resulting model is relatively simple and highly flexible to be applied for the complex system. By setting the PN model parameters, various operation strategies of smart microgrid can be evaluated simply. In order to show the effectiveness of the proposed model, numerical simulations have been carried out.

Key words: Hybrid petri net, complex system, smart microgrid, model, analyze, carried

INTRODUCTION

Access to affordable and reliable electricity supply is a key determinant to ensure socioeconomic development and community prosperity. However, in 2015 one-in-six people in the world lack access to electricity. Most of them lives in Asia and Africa and some of them lives in areas which are endowed by abundant renewable energy resources. Although, the infrastructure of electric power supplies has been developed, conventional systems which are large-scale equipment utilization, centralistic wide-area operation and largely fossil fuel dependent cannot address the problem effectively. Nowadays, small scale electric distribution grid called microgrid is providing some opportunities particularly in developing countries for maximizing local energy resource use increasing access and enhancing reliability (Williams *et al*., 2015).

Beside microgrid issue, electric power industries are facing new challenge as a consequence of technology advancements and need changes of society. Electric power systems are being prepared by their stakeholders to become smart grid system. Although only few number of smart grid are being deployed now in near future the evolution to smart grid will occur widely not only in developed countries but also in developing countries (Tuballa and Abundo, 2016). Development of advanced technologies like power electronics, communication and information technologies which are suitable for smart grid will accelerate the evolution. Through these technologies smart grid will be able to monitor and manage rapidly and intelligently electricity supplies from various power sources to meet varying consumer demands. Also, hopefully smart grid will operate in cost-effective, low environmental impacts while maximizing reliability, resiliency and stability.

Smart microgrid composes of main physical components that are distributed generators, loads, energy storages and distribution networks. These components are connected and coordinated in such a way by central or distributed management systems via. communication-information networks (Aman *et al*., 2013). Generally, a conceptual model of smart microgrid can be depicted in Fig. 1. Loads may be electric cars, building electric equipment industry's utilities, home electronic appliances, etc. and can be classified as controllable and uncontrollable loads. Distributed generators can be classified into renewable and non-renewable sources. Energy storages can function as loads or power generators depending on energy quantities stored. Furthermore, smart grid may be connected to utilities or operate independently. All these components are monitored and controlled in optimal way by central or distributed control system.

One of the problems of smart microgrid system is the number of the main components composed. Larger component number increases component-interactions and the smart microgrid becomes more complex. Moreover, the complexity of smart microgrid arises due to distributed nature of monitoring and control devices installed in various location (Mahmood *et al*., 2015). Consequently, control strategies of complex smart microgrid are also hard to design and evaluate. Several examples of control strategies can be found in some research publications. For

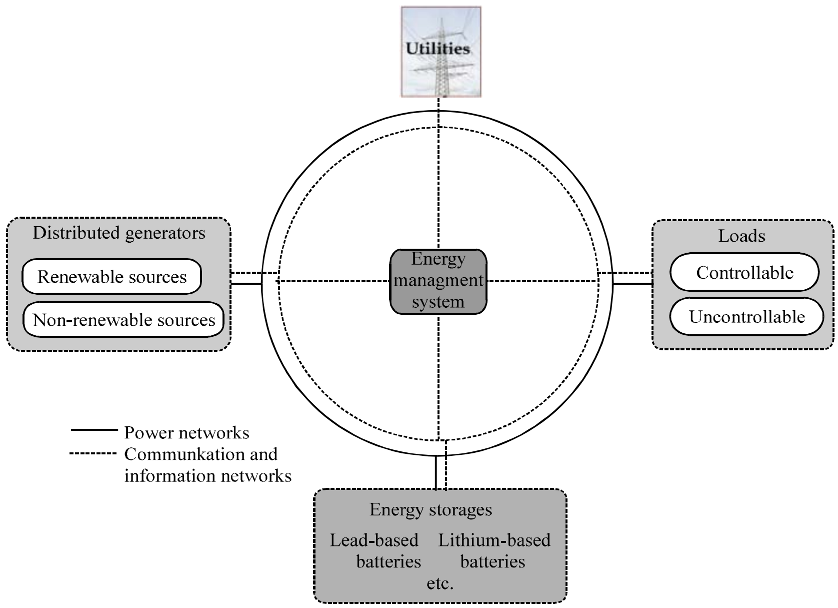

Fig. 1: Conceptual Model of smart grid

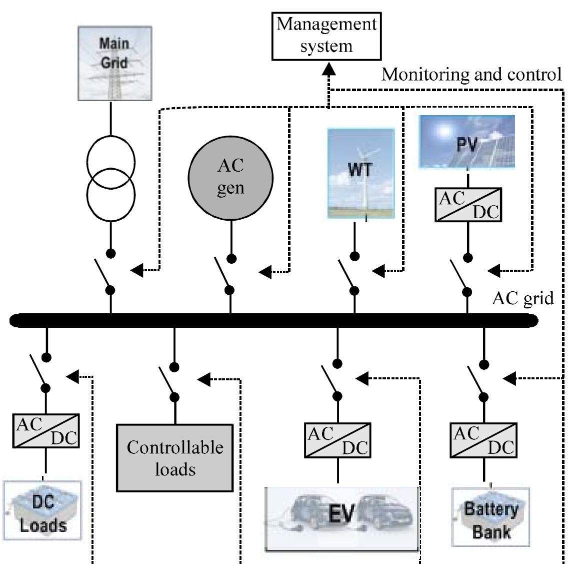

Fig. 2: Switch controlled smart microgrid system

example, few researchers (Hittinger *et al*., 2015; Elsayeda *et al*., 2015) have used if-than-based strategies to control on-off switch of the system as shown in Fig. 2. It is obvious that it is so hard to evaluate the effectiveness of the strategies if the switch number increases.

Complexity has become big issue in smart microgrid. Many research results have been published to address the issue. It can be summarized that researchers emphasize the need of modeling tools for designing and analyzing complex smart microgrid (Rylatt *et al*., 2015). One of the mathematical models that has been intensively applied is agent system model (Rylatt *et al*., 2015; Larsen *et al*., 2013). Another model called petri net has begun to be used to model smart microgrid (Lu *et al*., 2016; Halim, 2016). Lu *et al*. (2016) have used hybrid petri net to model distributed generators including photovoltaic and wind turbine. However, the model proposed is complex and it is difficult to be applied for large number of microgrid components. Different to the Lu's works, Halim has explored the use of time continuous petri net for modeling microgrid. The proposed model is relatively simple, however, the model is effective for limited size microgrid.

Petri net has some advantages over other models because of its ability to express concurrent and synchronized systems. Petri net has been applied for modeling concurrent complex systems such as transportation systems, biological systems and electrical systems. In the field of power system analysis, applications of petri net are various like analysis of protection system (Jamil, 2004). In this study, a new application of hybrid petri net is provided for modelling complex smart microgrid. The model is derived from node's power balance principal. The proposed model can be used to analyze the system operation in various modes. Specifically, the model developed can be deployed for evaluating the effectiveness of control system as shown in Fig. 2. The performance of the model will be verified by using numerical simulation.

MATERIALS AND METHODS

Petri Net (PN) is a graphical and mathematical system description introduced firstly in 1962 by Carl Adam Petri to represent a discrete event system. Discrete PN is the original version of PN Model. As the theory being developed, continuous PN becomes alternative version. Graphical representation of PN is shown in Fig. 3. Basically, PN consists of the components that are place, transition and arc. As shown in the Fig. 3, different symbols are utilized for discrete and continuous PN, P_1, P_2 are discrete place, P_3, P_4 are continuous place, t_1, t_2 are discrete and continuous transition respectively. Place represents system state variable, while its value is called marking that is represented by black dot (Fig. 3). The marking of the place changes by firing of transitions. Transition can fire if it satisfies a condition. Discrete PN allows non-negative integer values of marking while continuous PN allows nonnegative real values. Changes of the marking depend on the number of arcs connected between places and transitions. Detail description of basic PN can be found by Murata (1989).

Before describing the model proposed, two definitions of petri net structures are provided. Detail descriptions can be found by Silva and Recalde (2002).

Definition 1: Untimed Discrete Petri Net (UDPN) is a structure of PN denoted as $\langle N, m\rangle$ where $N = \langle P, T, Post\rangle$ is a net structure with P: a set of q places T: a set of r transitions, Pre: $P\times T\rightarrow\mathbb{N}$ and Post: $P\times T\rightarrow\mathbb{N}$ are pre and post incidence matrices that specify the arcs and $m_0\in\mathbb{N}^q$ is the initial marking vector ($\mathbb{N}$ is the set of non-negative integers).

A transition $t_j\in T$ is enabled if and only if $\forall p_i\in{}^\times t_j$, m $(p_i)>$ Per (P_i, t_j) (t_j is set of input places of a given transition t_j). If transition_j is enabled, the firing of transition takes place simultaneously and the marking will evolve as following Eq. 1:

$$m = m_0+C\times\sigma \quad (1)$$

Where:

σ: $T\rightarrow N$ = The firing count vector
m: $P\rightarrow N^q$ = The marking vector
C = Post-Pre = The incidence matrix

Definition 2: Timed Continuous Petri Net (TCPN) is a structure of PN denoted as $\langle N, m_0\rangle$ where $N = \langle P, T, Post\rangle$ is a net structure with P: a set of q places, T: a set of r transitions, Pre: $P\times T\rightarrow\mathbb{N}$ and Post: $P\times T\rightarrow\mathbb{N}$ are pre and post- incidence matrices that specify the arcs and $m_0\in\mathbb{R}^q_{0+}$ is the initial marking vector ($\mathbb{R}_{0+}$ is the set of non-negative real numbers).

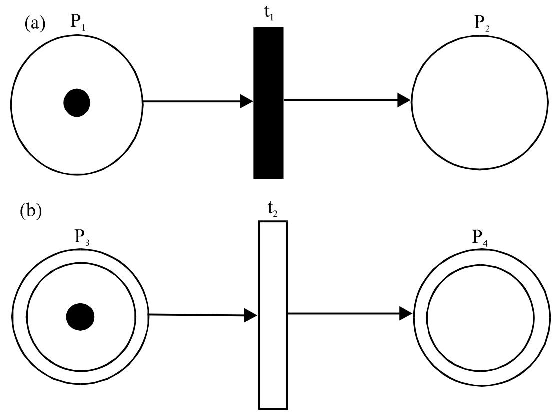

Fig. 3: Graphical representation of PN structure; a) discrete PN and b) Continuous PN

A transition $t_j\in T$ is enabled if and only if $\forall p_i\in{}^\times t_j$, m $(p_i)> 0$. If transition is enabled, the marking will evolve as following state (Eq. 2):

$$\dot{m}(\tau) = C\times f(\tau) \quad (2)$$

Where:

τ = The represents time
$\dot{m}(\tau)$ = The derivative of m (τ) with respect to time
m $(\tau)\in\mathbb{R}^q_{0+}$ = The marking vector
C = Post-Pre = The incidence matrix
f (τ): $T\rightarrow\mathbb{R}^q_{0+}$ = The flow vector of transitions

The flow of a transition t_i at instant τ is defined as:

$$f[t_t](\tau) = \lambda[t_i]\times enab(t_i, m(\tau)) \quad (3)$$

where, enab:

$$(t_i, m(\tau))\min_{p\in{}^\times t_i}\left\{\frac{m[p]}{Pre[p, t_i]}\right\}\lambda[t]\in\mathbb{R}>0$$

is the firing rate of transition in this study Hybrid PN is defined as PN that contains UDPN and TCPN.

Basic PN structures used: Some PN structures used for modeling smart microgrid are provided in this section. The aims of is this section is to give mathematical models of some PN Structures and their properties.

PN structure 1: Structure 1 is Hybrid petri net shown in Fig. 4. P_3, P_4 are discrete places and P_1, P_2 are continuous places. t_1 is continuous transition, t_2 and t_3 are discrete transition. State evolution as firing of transition t_1 is:

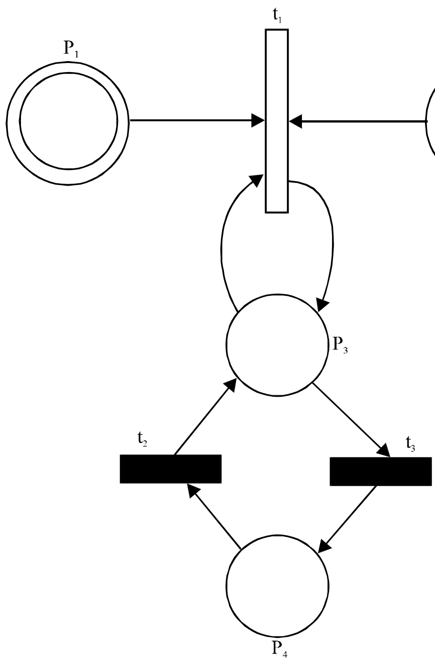

Fig. 4: PN structure 1

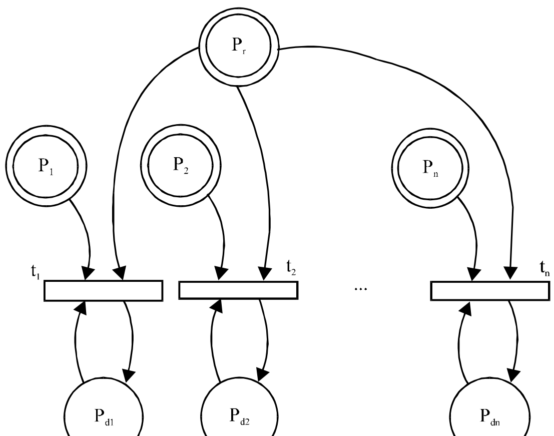

Fig. 5: PN structure 2

$$\dot{m}(\tau) = C \times f(\tau)$$

Where:

$$m(\tau) = \left[m[p_1](\tau), m[p_2](\tau) m[p_3](\tau)\right]^T, C = [-1\text{-}\ 0]^T,$$
$$f[t_1](\tau) = \lambda[t_1]\min\{m[p_1](\tau), m[p_2](\tau), m[p_3](\tau)\} \quad (4)$$

It can be verified from Eq. 4 that marking in P_3 is unchanged.

PN structure 2: Structure 2 is extended type of PN Structure 1. Structure 2 as shown in Fig. 5 has n+1 continuous places, n continuous transitions and n discrete places noted as P_{di}. For emptying a place p_i, i = 1, ..., n faster than others, it can be done by controlling the flow of associated transition t_i larger than others. For simplicity, it is assumed that:

$$f[t_1](\tau) > f[t_2](\tau) >, ..., > f[t_n](\tau) \quad (5)$$

And:

$$m[p_1](\tau) + m[p_2](\tau) + ,..., + m[p_2](\tau) \le m[p_r](\tau) \quad (6)$$

then the following equation can be derived:

$$\begin{aligned} &\lambda[t_1]\min\{m[p_1](\tau),\ m[p_{dn}](\tau)\} > \\ &\lambda[t_2]\min\{m[p_2](\tau),\ m[p_{d2}](\tau)\} >, ..., > \\ &\lambda[t_n]\min\{m[p_n](\tau),\ m[p_{dn}](\tau)\} \end{aligned} \quad (7)$$

Regarding Eq. 7, the next two conditions can be encountered. Condition 1 when m $[p_i]$ (τ) <m $[p_{di}](\tau)$, i = 1, ..., n. Then, $\lambda[t_1]$ m $[p_1](\tau) > \lambda[t_1]$ m $[p_2](\tau) >, ..., > \lambda[t_n]$ m $[p_n](\tau)$. It is obvious that the magnitude of each flow depends on firing rate of t_i and markings of places p_i.

Condition 2 when m $[p_i]$ (τ) >m $[p_{di}](\tau)$, i = 1, ..., n Then $\lambda[t_1]$ m $[p_{d1}](\tau) > \lambda[t_2]$ m $[p_{d2}](\tau) >, ..., > \lambda[t_n]$ m $[p_{dn}](\tau)$. It is obvious that the magnitude of each flow depends on firing rate of t_i and markings of places p_{di}.

PN structures of smart microgrid: Using the above PN structures, the components of smart microgrid can modeled as follows.

PN Model for power balance in a bus: The proposed model follows PN structure 1 as described in the previous study and is shown in Fig. 6ab. P_s is place for representing power source and p_L is for modeling power load. P_{sw1} and p_{Sw2} represent switch-on and off states, respectively. If p_{Sw1} holds a marking and initial condition of place p_S (0) and p_L (0) # 0, then transition t is enabled and firing.

PN model for power balance in multiple buses: Power source can supply electricity to multiple load buses by applying PN structure 2. Referring to Fig. 5, p_r, p_i and p_{di} with i = 1, ..., n express power source, loads and simplified on-off switch, respectively. By setting firing rates properly, power source can be prioritized for supplying one load than other.

PN Model for multiple power sources supplied to a bus: To model multiple power sources connected to a bus, PN

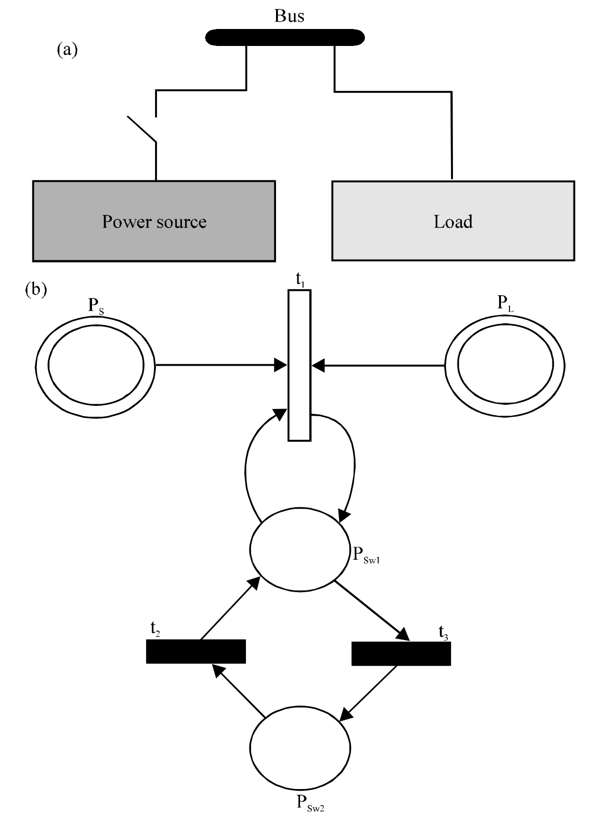

Fig. 6: PN model for switched power flow balance in bus; a) System to be modelled and b) Associated PN Model

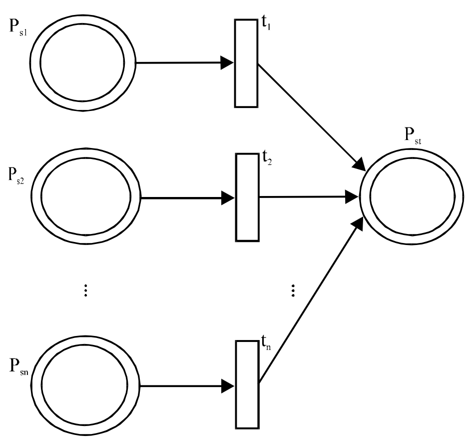

Fig. 7: PN Model for n power sources

as in Fig. 7 is used. Figure 7 displays n power sources p_{S1}, p_{S2}, ..., p_{Sn}. Place p_{St} is total electric power collected from each source for supplying to a bus.

PN Model for multiple loads connected to a bus: The PN Model of multiple electric loads connected to a bus is

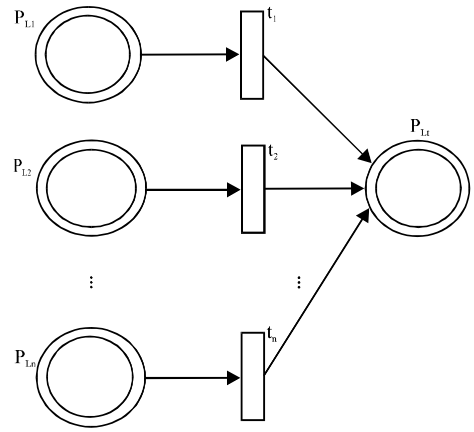

Fig. 8: PN Model for n lLoads

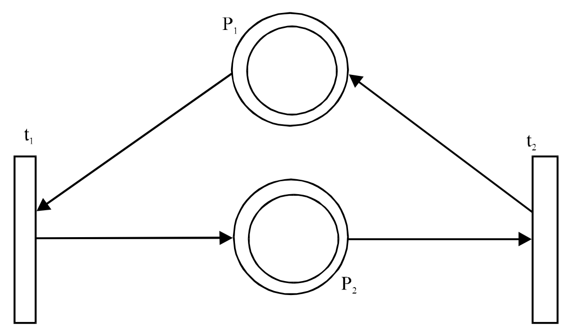

Fig. 9: PN Model for storage system

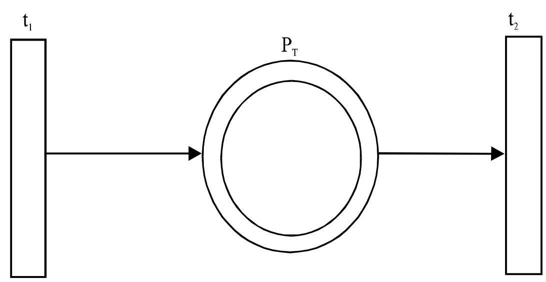

Fig. 10: PN for distribution Line

shown in Fig. 8. Figure 8 shows that there are n electric loads represented by place p_{L1}, p_{L2}, ..., p_{Ln}. Place p_{Lt} is total loads connected to a bus.

PN Model for storage system: Storage system can be represented by petri net as displayed in Fig. 9. P_1 is discharged capacity while p_2 is charged capacity. It can be verified that $m[p_1]+m[p_2]$ = constant.

PN for distribution line: Power distribution line can be modelled by PN as depicted in Fig. 10.

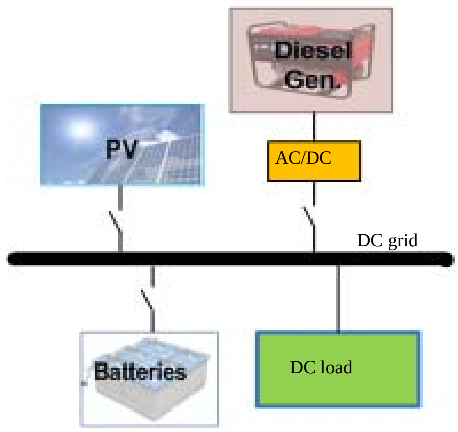

Fig. 11: System 1 of smart microgrid

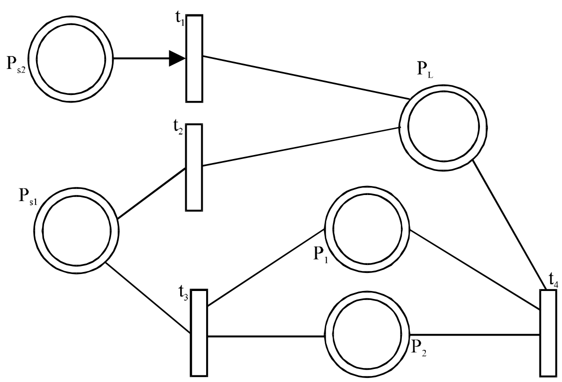

Fig. 12 PN model of system 1

Studied systems: Two studied systems are taken into account to verify the effectiveness of the proposed model

System 1: System 1 is shown in Fig. 11. The system consists of Photovoltaic (PV), batteries, DC load and diesel generator. All power sources are connected by switches which can be controlled to follow a predefined operation strategy.

PN Model for system 1 is displayed in Fig. 12. In this figure, p_{S1}: output power of PV; p_{S2}: output power of diesel generator; p_L: DC load; p_1, p_2 represent battery condition. To convert physical quantity of electric power to marking number of PN Model in system 1, it is set that 1 marking is equivalent to 1 kW of electric power. Pre and Post matrices are:

$$Pre = [0,1,1,0;1,0,0,0;0,0,1,0;0,0,0,1;1,1,0,1]$$
$$Post = [0,0,0,0;0,0,0,0;0,0,0,1;0,0,1,0;0,0,0,0]$$

System 2: The system studied is shown in Fig. 13. The syste m consists of two zones and each zone connected to main grid through transmission line. Each zone composes of renewable power sources and AC loads without energy storages. For simplifying the figure, on-off switches connecting power sources to nodes are not displayed.

PN for system 2 is displayed in Fig. 14. In this Fig. 14, p_{S1_1}: power of PV in zone 1; p_{S1_2}: WT power in zone 1; p_{S2_1}: power of PV in zone 2; p_{S2_2}: WT power in zone 2; p_{S1_t}: total power of zone 1; p_{S2_t}: total power of zone 2; p_{L1}: AC load in zone 1; p_{L2}: AC load in zone 2; p_{T1}, p_{T2}: distribution line connected main grid with zone 1 and 2; p_S: power of main grid. In system 2, it is assumed that 1 marking is equivalent to 1 kW of power.

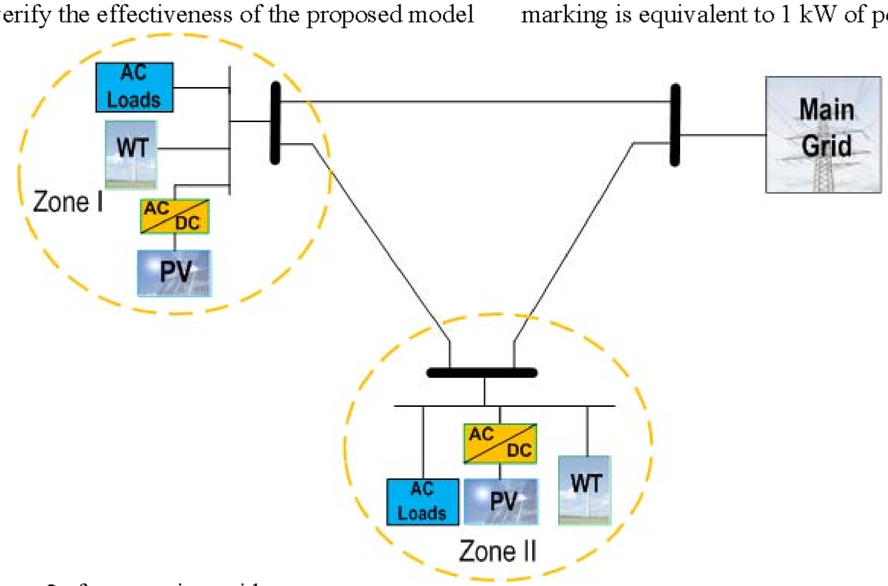

Fig. 13: System 2 of smart microgrid

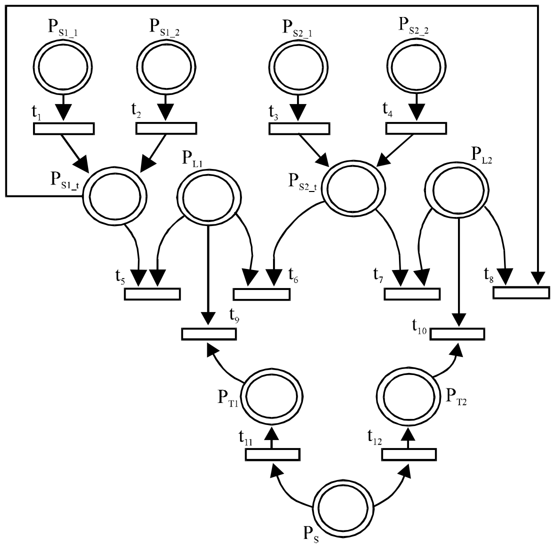

Fig. 14: PN Model for system 2

RESULTS AND DISCUSSION

In this study, numerical simulations of PN Models of system 1 and 2 are carried out to show the effectiveness of the proposed model. The simulation consists of four steps which are:

- Assuming the profiles of one-day load and renewable power supplies
- Setting the operation strategy of system studied
- Setting each firing rate of transition according to operation strategy adopted
- Simulating the PN Model

Following these four steps, the simulation results are as follows

System 1: Profiles of one-day DC load and PV are set as shown in Fig. 15. It can be verified that from 6-8 am and 4-6 pm, DC load is larger than PV power supply.

Operation strategy of the system are as follows:

- If PV power is available sufficiently, the power is prioritized for supplying firstly to DC load and secondly to battery
- Power from battery is used to supply to DC load if PV power is not enough
- If PV power and battery power are not sufficient for supplying DC load, then the power is provided from diesel generator

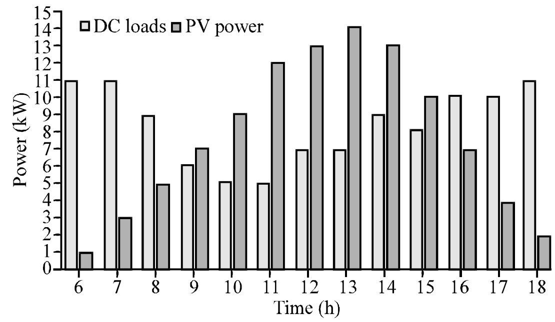

Fig. 15: Profiles of DC load and PV power for system 1

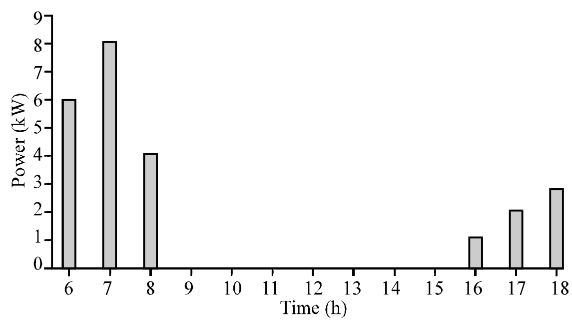

Fig. 16: Diesel generator power supplied

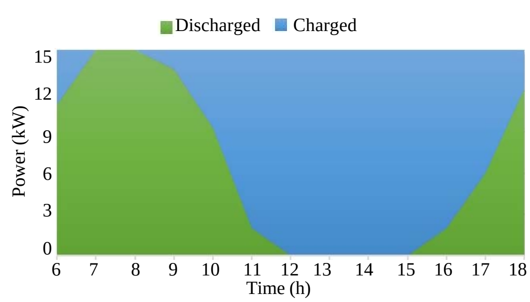

Fig. 17: Battery state evolution

The above strategy can be implemented by if-then rule base control switch:

- To implement the above operation strategy, the firing rate of each transition is taken as $\lambda[t_1] = 20$, $\lambda[t_2] = 300$, $\lambda[t_3] = 100$, $\lambda[t_4] = 50$
- To simulate PN Model, 1 kW of power and load are converted to one marking. It is also assumed that the remining battery's power is 4 kW in initial condition

Simulation results of PN Model are in form of marking evolution. The markings are converted to power and the results are shown in Fig. 16 and 17. Figure 16 is graph presenting the power of diesel generator supplied and Fig. 17 is the condition change of battery. It is clear from

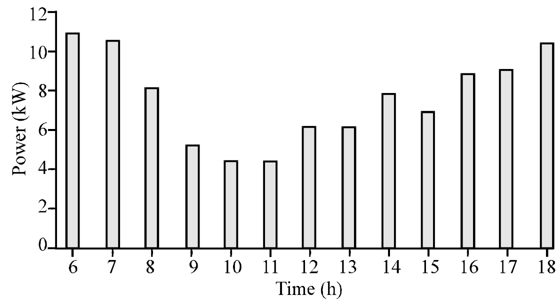

Fig. 18: Power supplied by diesel generator; a) Zone 1and b) Zone 2

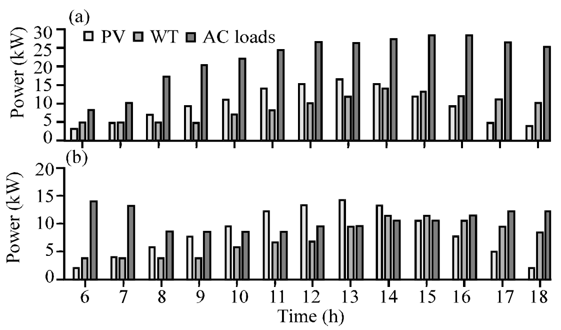

Fig. 19: Profiles of loads and sources; a) Power supplied from main grida and b) Inefficient use of renewable powers

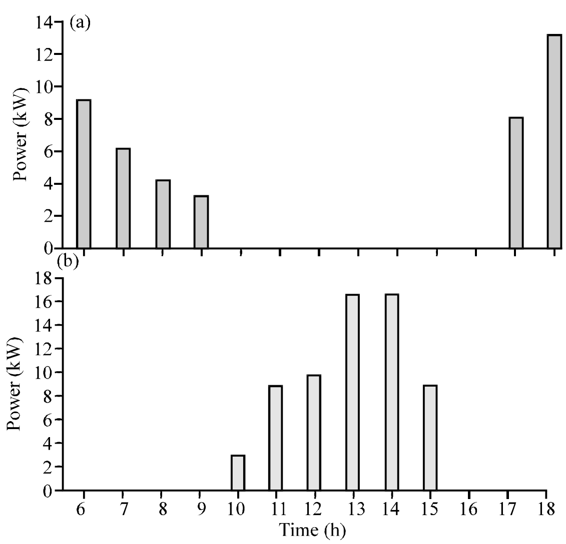

Fig. 20: Supplying characteristics of power sources

the graphs that the diesel generator is responsible for supplying electricity during PV and batteries power are not enough.

Different strategy of system 1 operation can be evaluated. By setting that power from diesel generator is most prioritized for supplying to DC load and battery, firing rate of each transition is taken as $\lambda[t_1] = 300$, $\lambda[t_2] = 50$, $\lambda[t_3] = 200$, $\lambda[t_4] = 1$. The simulation results are given in Fig 18. Figure 18 shows that the diesel generator provides more power to DC load.

System 2: Profiles of one-day AC load and RE sources of each zone are given in Fig. 19. Different load profile is defined for each zone. Operation strategy of the system are as follows. Renewable power sources in each zone are most prioritized to supply AC loads in the associated zone. Renewable power can be transferred from zone that has exceed power to lack power. If renewable powers in all zone are not enough for supplying all AC loads then the power will be supplied from main grid.

To implement the above operation strategy, the firing rate of each transition is taken as $\lambda[t_1] = 200$, $\lambda[t_2] = 200$, $\lambda[t_3] = 200$, $\lambda[t_4] = 200$, $\lambda[t_5] = 200$, $\lambda[t_6] = 50$, $\lambda[t_7] = 200$, $\lambda[t_8] = 50$, $\lambda[t_9] = \lambda[t_{10}] = \lambda[t_{11}] = \lambda[t_{12}] = 1$.

To simulate PN Model, 1 kW of power is converted to a marking. The simulation result is given in Fig. 20. It can be verified from Fig. 20 that supplying from main grid occurs during morning and evening. Furthermore in the mid-day, renewable powers are used inefficient way.

By setting different firing rates of the transitions, many different operation strategies of System 2 can be evaluated.

Even though two studied systems have been considered in this study, more complex smart microgrid systems can be modelled by proposed hybrid petri net. Moreover, not only switch controlling power source, relay for system protection and switch controlling load can be represented by proposed model with slightly modifications.

CONCLUSION

In this study, the capability of Hybrid petri net has been explored to represent smart microgrid. Some basic structures of PN have been presented based on the principal of power balance in a bus. To represent operating strategy of smart microgrid, firing rates as Hybrid PN parameter are used properly. By adjusting firing rates, the evaluation of various smart microgrid operation can be done. Although, two smart microgrid systems which are relatively simple have been studied, the proposed model can be applied for more complex system.

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