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ASSESSMENT OF THE RELIABILITY OF A DYNAMIC SMART GRID SYSTEM

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Abstract

One of the expectations from a smart grid is that it will be more efficient and reliable than a traditional power grid. The electric power distribution system is expected to change drastically. With the involvement of modern high-speed communication and computational applications, the speed with which one can monitor actions on a grid has increased. The incorporation of distributed renewable energy resources and storage systems have brought a new dynamic into this system. Smart grid technologies are expected to change the design and operating requirements of the electric power system, allowing current electricity grids to better incorporate renewable energy sources such as wind and solar power, backup distribution generators and advanced energy storage systems. To measure the reliability of such a system would require new tools and applications. This paper presents a new method of finding reliability and availability of the electric power distribution network; that is the ability to model the dynamics of the smart grid including a variation of weather conditions at different locations for the large-scale system. Dynamic reconfigurations of a smart grid and variable weather conditions create challenges in reliability modelling and analysis. To overcome these obstacles, a new approach has been developed – the variable weather Boolean logic driven Markov process.

Key Words

Power interruptions, Markov modelling, Boolean logic driven Markov process, power reliability, variable weather

1. Introduction

A smart grid consists of a variety of power components such as transformers, generators, overhead lines, renewable energy resources, energy storage elements and a micro grid. A smart grid will allow current electricity grids to incorporate better the renewable energy sources such as wind and solar power, backup distribution generators (DG) and advanced energy storage systems. Smart grid technologies are expected to change the fundamental design and operating requirements of the electric power system. To understand and analyze the impact that a smart grid has on power system operations and design, several issues have been identified:

(a) Current analysis and modelling tools must evolve to address the future's more interactive power system and to simplify engineering tools, to more efficiently handle smart grid technologies' related issues.
(b) New analytical methods/tools are needed to determine the effects of penetration of smart grid technologies on the operation of the power system as well as the resultant effects on the power system's quality, reliability and availability.
(c) Evaluation tools are required to define better the costs and benefits of the distributed resources to power system operations and dispatching.

The primary engineering tools for power system design and analysis are power flow and fault-current studies. While power flow modelling can predict the electrical properties of a smart grid, reliability modelling predicts the availability and interruption of such a system. Generally, smart grid engineering tasks can be divided into planning and design stages. The planning stage includes identifying system needs and limitations, proposing projects, resolving the issue(s) and gaining approval for projects; the design stage takes a project from concept to realization in a safe, efficient and cost-effective manner.

Reliability assessment is an evolving issue of increased importance. In the planning stage, the functions that enable reliability modelling are [1], [2] as follows

- Design a new system to meet the reliability target.
- Identify reliability problems on existing systems.
- Design a system that offers varying levels of reliability.

Reliability of the smart grid is one of the most important areas of reliability theory application. Random failures are certain to occur from time to time, especially when extremes in weather or other factors present hazards that the power system was not designed to withstand. Reliability methods provide important analytical tools that can be used to compare and evaluate smart grid design and performance. The models should be as simple as possible, but they must represent all features that are critical to system reliability. Reliability parameters vary from component to component and situation to situation. Component reliability data is one of the most important

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parameters of smart grid reliability assessment. In our research, we used reliability information based on historical utility data, manufacturer test data, professional organizations such as IEEE and Cigre, technical conferences and journal proceedings. Electrical equipment reliability data is usually obtained from surveys of individual industrial equipment failure reports. The collection of reliability data is a continuous process because of the critical nature of maintaining accurate updates [3]–[5].

The smart grid reliability indices are used to quantify sustained interruptions. Short-duration outages for some customers, such as hospitals and large industrial customers, can result in complex systems shutting down. In many cases, customers have installed backup generation or other means of addressing short-duration outages. In particular, it is these types of outages that would benefit from the presence of distributed generation and energy storage. Therefore, a reliability index should not only quantify enhanced reliability for sustained interruptions, but also quantify enhanced reliability for short-duration outages.

Dynamic reconfigurations of the smart grid and variable weather (VW) conditions create difficulties in reliability modelling and analysis. To overcome this obstacle, we analyzed distributed renewable generation sources with generator options using Markov modelling and Boolean logic driven Markov process (BDMP). The BDMP modelling approach offers advantages over conventional models because it allows complex dynamic models to be defined under VW conditions.

2. Methods and Data Processing

The basic modelling for availability can be seen in [6]. The Markov modelling and BDMP is used to develop VW-BDMP. The data was collected from various reliable resources. The following section describes the introduction of VW conditions to Markov modelling.

2.1 Markov Modelling of Smart Grid under VW Condition

The failure rates of smart grid components located in relatively fixed environments can be considered a constant during the useful life period. For transmission lines and other outdoor components, the environment is not a constant and can have a considerable effect upon their failure rates. These two states have a fluctuating environment covering normal and stormy weather with assumed exponential distribution functions. With these assumptions, the Markov approach can be applied to a single unit with a two-state failure environment [7]–[9].

To use this approach we have to define:

$\lambda, \mu =$ normal weather failure and repair rates

$\lambda', \mu' =$ stormy weather failure and repair rates

$m = \frac{1}{S}$ where S is the expected duration of stormy weather

$n = \frac{1}{N}$ where N is the expected duration of normal weather

The state space diagram for the Markov model with one component and VW conditions is shown in Fig. 1.

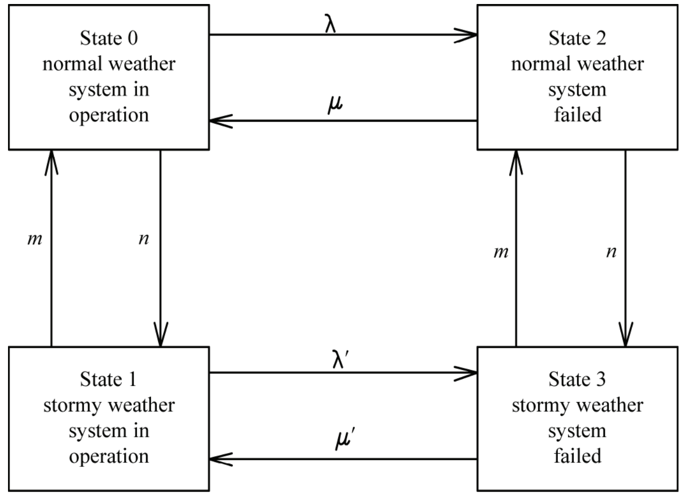

Figure 1. Single unit state space diagram.

Differential equations for this diagram in matrix form are:

$$\begin{bmatrix} P_0'(t) \\ P_1'(t) \\ P_2'(t) \\ P_3'(t) \end{bmatrix} = \begin{bmatrix} P_0(t) & P_1(t) & P_2(t) & P_3(t) \end{bmatrix} \begin{bmatrix} -(\lambda+n) & n & \lambda & 0 \\ m & -(m+\lambda) & 0 & \lambda \\ \mu & 0 & -(\mu+m) & n \\ 0 & \mu & m & -(\mu+m) \end{bmatrix} \tag{1}$$

The steady-state probabilities can be found from the matrix defined in (1).

$$\begin{aligned} -(\lambda+n)P_0 + mP_1 + \mu P_2 &= 0 \\ nP_0 - (m+\lambda')P_1 + \mu' P_3 &= 0 \\ \lambda P_0 - (\mu+n)P_2 + mP_3 &= 0 \\ P_0 + P_1 + P_2 + P_3 &= 1 \end{aligned} \tag{2}$$

For this system:

P (system operating) $= P_0 + P_1$, availability

P (system failed) $= P_2 + P_3$, unavailability

Implementation of smart grid technologies into the power system creates a completely new structure, the smart grid. Evaluations and analysis of smart grid reliability with dynamic reconfiguration and VW conditions with existing analytical tools and methods is presently not possible; thus, new modelling tools and techniques must be developed. The goal can be achieved by formulating a new method which combines techniques used for the analysis of dynamic systems and techniques of a power system with VW conditions. We developed a new method called the VW-BDMP. This innovation combines two modelling techniques: Markov modelling and the modelling of VW conditions. The BDMP modelling approach offers advantages over conventional models because it allows complex dynamic models to be defined under VW conditions.

The failure rates, the switching rates and the repair rates are a reciprocal of the mean time to fail (MTTF), mean time to switch (MTTS) and mean time to repair (MTTR).

$$\lambda = \frac{1}{MTTF}; \quad \text{failure rate}$$
$$\sigma = \frac{1}{MTTS}; \quad \text{switch rate}$$
$$\mu = \frac{1}{MTTR}; \quad \text{repair rate}$$

3. Analysis, Modelling and VW-BDMP

The smart grid can offer substantial benefits through the integration of different technologies, such as renewable energy, storage batteries, power and control electronics. A smart grid brings better operation of a power system in terms of power losses and reliability. In this section, we will analyze the smart grid under VW conditions.

We will use methods described in [6] and as explained earlier. The grid is analyzed using BDMP (under VW conditions), in our case of normal weather and stormy weather. In the main smart grid system, we have several subsystems: system with DG, system with battery storage and photovoltaic, system with wind generator and battery storage, and static transfer switch.

The reliability of all subsystems can be analyzed in isolation and/or in cooperation. The demonstration of the new method, VW-BDMP, is shown on the system with DG (Fig. 2). The systems can be analyzed in many different ways such as with no influence of weather [6], no smart grid elements, with smart grid elements and normal weather and with the smart grid elements and stormy weather. As for the reliability indices, we will consider the availability and unavailability of the power supply to the particular consumer, either industrial, commercial or residential.

3.1 System with No DG and with Normal Weather Conditions

DG can have an influence on the systems' reliability. There are many technologies used for DG, including renewable energy (wind-powered induction generators, photovoltaics, small hydro), gas turbine-driven synchronous generators, fuel cells and others. The system we considered consists of the following:

- L – overhead transmissions line
- T – power transformer
- DG
- load

Here we are focusing on the most common applications, for example, backup generation, used in hospitals, shopping centres, *etc*. The basic connection is shown in Fig. 2. The DG remains offline during normal operation and is started if the utility supply is interrupted to feed the critical load.

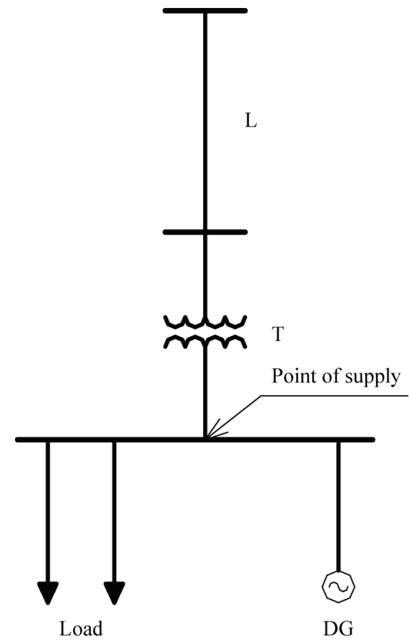

Figure 2. System with DG single line diagram.

Parameter values for Markov models of the system with DG and normal weather conditions:
$\lambda_L = 0.75\,\text{yr}^{-1}$ $(8.561 \times 10^{-5}\,\text{h}^{-1})$
$\mu_L = 0.25\,\text{yr}^{-1}$ (MTTR $= 4\,\text{h}$)
$\lambda_T = 0.34\,\text{yr}^{-1}$ $(0.00000388\,\text{h}^{-1})$
$\mu_T = 0.0167\,\text{yr}^{-1}$ (MTTR $= 60\,\text{h}^{-1}$)

The system has the same structure as the system with no weather conditions. The Markov state space diagram of the system is the same, and so is the transition matrix. The solution for the steady-state probabilities are:

$$\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{bmatrix} = \begin{bmatrix} 0.999652147 \\ 0.000335545 \\ 0.000142886 \\ 9.297 \times 10^{-8} \end{bmatrix} \tag{3}$$

For this system:
P (availability of power supply) $= P_0 = 0.99952147$
P (unavailability of power supply) $= P_1 + P_2 + P_3 = 0.000478524$

3.2 System with DG and No Influence of Weather

Parameter values for the Markov model of a system with DG and no weather conditions:
$\lambda_L = 0.5\,\text{yr}^{-1}$ $(0.0000517\,\text{h}^{-1})$
$\mu_L = 0.25\,\text{yr}^{-1}$ (MTTR $= 4\,\text{h}^{-1}$)
$\lambda_T = 0.34\,\text{yr}^{-1}$ $(0.00000388\,\text{h}^{-1})$
$\mu_T = 0.0167\,\text{yr}^{-1}$ (MTTR $= 60\,\text{h}^{-1}$)
$\lambda_G = 0.2\,\text{yr}^{-1}$ $(0.00000228\,\text{h}^{-1})$
$\mu_T = 0.125\,\text{yr}^{-1}$ (MTTR $= 8\,\text{h}^{-1}$)

Differential equations for this diagram in matrix form are:

$$
\begin{bmatrix} P_0'(t) \\ P_1'(t) \\ P_2'(t) \\ P_3'(t) \\ P_4'(t) \\ P_5'(t) \end{bmatrix} = \begin{bmatrix} -(\lambda_L+\lambda_T) & \mu_L & \mu_T & 0 & 0 & 0 \\ \lambda_L & -(\lambda_T+\mu_L+\lambda_G) & 0 & \mu_T & 0 & 0 \\ \lambda_T & 0 & -(\mu_T+\lambda_L) & \mu_L & 0 & 0 \\ 0 & \lambda_T & \lambda_L & -(\mu_L+\mu_T+\lambda_G) & 0 & \mu_G \\ 0 & \lambda_G & 0 & 0 & -(\mu_G+\lambda_T) & \mu_T \\ 0 & 0 & 0 & \lambda_G & \lambda_T & -(\mu_G+\mu_T) \end{bmatrix} \begin{bmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \\ P_3(t) \\ P_4(t) \\ P_5(t) \end{bmatrix} \tag{4}
$$

Using BDMP, described in [6], the state space diagram, in Fig. 3 is:

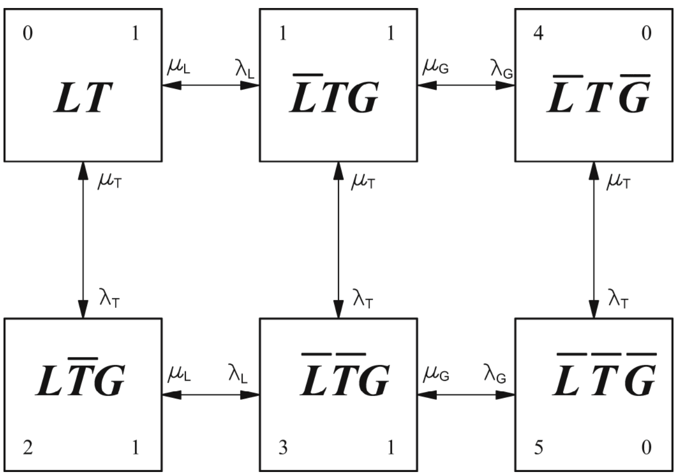

Figure 3. State space diagram for system with DG no weather conditions.

The steady-state probabilities can be found by solving (4):

$$
\begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} = \begin{bmatrix} 0.9974487 \\ 0.0002278 \\ 0.0023228 \\ 5.305E-07 \\ 4.55E-08 \\ 9.67E-11 \end{bmatrix} \tag{5}
$$

For this system:
P (availability of power supply) $= P_0 + P_1 + P_2 + P_3 =$ 0.999999958
P (unavailability of power supply) $= P_4 + P_5 =$ 4.165E−08

4. Conclusions

The reliability of a smart grid under VW conditions is analyzed with a newly developed methodology, VW-BDMP. The analyzed smart grid consists of several subsystems: system with DG, system with battery storage and photovoltaic, and a system with wind generator and battery storage. The reliability of all subsystems is analyzed separately. The subsystems can be analyzed with no influence of weather, with no smart grid elements, with smart grid elements and normal weather, and with the smart grid elements and stormy weather. For reliability, the indices considered are availability and unavailability of the power supply to the particular consumer – industrial, commercial, or residential. The results show improvement of the reliability indices with the smart grid technologies and also show the influence of the weather. The weather, as expected, has a negative influence on the reliability of the smart grid.

The VW-BDMP shows tremendous progress in analyzing the dynamic smart grid system. Further work is ongoing by researchers to expand this method to other smart grid topographies.

References

[1] R.E. Brown, *Electric power distribution reliability.* (Boca Raton, FL: CRC Press, 2009).

[2] P.A. Anderson, *Power system protection.* (IEEE Press: Piscataway, NJ, 1999).

[3] B.S. Dhilon, *Power system, reliability, safety and management.* (Ann Arbor Science Publishers, Ann Arbor, MI, USA, 1983).

[4] IEEE Std 493-1997, IEEE recommended practice for the design of reliable industrial and commercial power systems, 1998.

[5] J.W. Aquilino, Report of transformer reliability survey – Industrial plants and commercial buildings. *Presented at Industrial and Commercial Power System Conference*, Houston, TX, 1981.

[6] A. Islam, A. Damnjanovic, and A. Domijan, Jr., Reliability of a dynamic distributed smart grid system, *Presented at the IASTED Power and Energy Systems – Africa PES 2010*, Gaborone, Botswana, SA, 2010.

[7] R. Billinton and K. Bollinger, Transmission system reliability evaluation using Markov Process, *IEEE Transactions on Power System and Apparatus*, *87*(2), 1968, 538–547.

[8] R. Billinton, *Power system reliability evaluation.* (Newyork, NY: Gordon and Breach Science Publishers, 1970).

[9] R. Billinton and R.E. Allan, *Reliability evaluation of power systems* 2nd ed. New York, NY: Plenum Press, 1996.

Biographies

Arif Islam received his B.Tech. degree in Electronics Engineering from A.M.U., India, and M.S. degree in Electrical and Computer Engineering from University of Florida, Gainesville, and Ph.D. degree in Electrical Engineering from University of South Florida, Tampa. He joined Siemens in 1994 and has worked in the industry for more than a decade executing many multi-million dollar projects. He enjoys research and produces time-bound results utilizing knowledge, experience, and management tools learnt while achieving an MBA degree. He is now at the State University of New York at Buffalo, NY, as a professor and deputy director of the Power Center for Utility Explorations and the Power and Energy Applied Research Laboratory. His fields of interest include power reliability, smart grid technologies, power electronics, motors and drives systems, understanding natural and manmade hazards, and fiscal evaluation of alternative resources of energy.

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