Contingency Ranking in Power Systems Via Reliability Rates

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***Abstract*—This paper shows the scope of probabilistic contingency ranking algorithms when applied to transmission systems with high levels of renewable integration. Using our fast screening contingency ranking algorithm, a performance index is calculated through AC power flows. In order to capture the probabilistic behaviour of the system outages, we use the reliability data from the Reliability Test System, and combined with the performance index this yields a different assessment on the contingency ranking task. The contingency ranking is applied in this paper for an N-1 security criterion. The entire model was developed and implemented for steady-state power system simulations using the MATPOWER programme which runs in MATLAB environment.**

I. Introduction

The UK is going through a period of expanding levels of integration from renewable energy sources (RES) as expected by the National Grid's Future Energy Scenarios (FES) [1], [2]. The rising levels of RES penetration into the transmission network coupled with an increase in distributed generation penetration across all voltage levels will require a rethinking to conventional approaches used by transmission system operators (TSOs) for estimating levels of network operational security.

All these new challenges call for a new flexible operational regime to be adapted by the TSO to meet variations in demand and supply at all times [3]. Maintaining the security in the system will be paramount for the correct functioning of the flexible grid of the future with high levels of RES and DG integrated.

To determine the severity of a contingency in the system, we implemented and added a contingency ranking algorithm in Matpower. This computation allows us to rank which contingencies are the most severe. Using an AC power flow algorithm we get the state variables for each state scenario. These output variables are used to get two indices, one that measures the severity and post contingency loadability of transmission lines, and one that assesses the severity of bus voltages violations. All calculations are carried out whilst upholding an N-1 criterion as this is the current level of security upheld by most TSOs including the UK's National Grid.

We use the updated IEEE Reliability Test System [4] which is essentially a three-area system with renewable energy resources integrated, and updated thermal limits for lines as well as load injections. Using a state sampling approach, we get the state probabilities for each N-1 scenario. Combined with the performance index under each condition, this results in the actual risk of the system, which combines severity and probability for a scenario. Using the contingency ranking weighted by probabilities of each outage scenario will give the TSO a powerful analytical tool for ranking contingencies in the order of their risk.

The paper is organised as follows. Section I contains the introduction. In section II we describe the modelling of contingency ranking algorithms used in this work, as well as the different criteria used whilst using them, mainly focused in the control room from TSOs in real time. Section III covers the probabilistic approach used in this work and its modelling. In section IV we show the simulation and results obtained. Finally; in section V we draw the conclusions.

II. Contingency ranking algorithm

In this work, we use an AC load flow algorithm [5], [6] to determine thermal limit violations in a post-contingency scenario. We calculate the performance index for each scenario under the N-1 criterion. The most critical scenarios are identified through a scattered plot according to the performance index value. Using the reliability data from the IEEE three area system system [4], [7], we obtain the probability of each N-1 branch outage case. Probabilities for each case are calculated with state enumeration [8], [9], and these probabilities are compared to Monte Carlo simulation [10]. The main purpose of this comparison is that the Monte Carlo simulation allows to observe the

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full behaviour of the system under possible contingencies scenarios. In our case it is restricted to a N-1 case, but other cases can happen.

The product of the performance index and the probability for each case gives a reliability performance index, which includes the probability of the contingency and severity. At the final part of the simulation, we calculate the conditional expected value of the performance index and this is compared to the value obtained from Monte Carlo simulation.

A. Performance Index: Thermal Violations

We calculate the performance index [11]–[13] that indicates the severity of a contingency as follows (1):

$$PI(P_1, P_2, \ldots, P_n) = \sum_{k \in lines} w_k \left(\frac{P_k}{P_k^0} \right)^{\alpha} \tag{1}$$

where

- k is the line or branch number,
- $w_k \in [0, 1]$ is the weight factor for each line,
- P_k is the active power flowing through the line,
- P_k^0 is the practical operational limit of the branch,
- $\alpha > 1$.

Eq. (1) is calculated for each N-1 condition scenario. The weight factor can be selected by the operational necessities of the TSO, since the topology of the grid is changing through the day, whether it is because of scheduled maintenance or fortuitous events in the system. The use of α helps to avoid the so called masking effect in contingency ranking. This effect consists on wrongly ranking contingencies above ones that should be in the top of the rank [10].

B. Performance Index: Bus Voltage violations

Since AC power flow algorithm is being used in this work, bus voltage levels are available at every power flow study. The contingency remains the same, branch outage, but now the observed variable is different. The performance index for voltage analysis [14] yields a measure on the severity when an abnormal voltage is presented, either this is because of a branch outage and a redistribution of load flows is the result, or a trip of generation unit(s) in the system. The next performance index for voltage analysis (PI_v) is shown in (2):

$$PI_v = \sum_{b \in PQ} w_{v_b} \left(\frac{|V_b| - |V_b^0|}{\Delta V_b^0} \right)^{\alpha} \tag{2}$$

where

- b is the PQ bus number,
- $w_{v_b} \in [0, 1]$ weight factor for each bus,
- V_b voltage magnitude of bus b in post contingency state,
- V_b^0 voltage magnitude of bus b specified in pre contingency state (usually 1 PU),
- ΔV_b^0 voltage deviation tolerance and

And this is calculated for each N-1 scenario. The voltage deviation tolerance can be interpreted as the allowable change in bus voltages whilst maintaining the system under security thresholds. This will depend in the operational scenario the system is found, which can be normal, alert, emergency or restorative [15]. Usually, for a normal state a $\pm 5\%$ is accepted; whilst for a state different from normal, the system should withstand $\pm 10\%$ some minutes at such condition. This will also depend on the voltage level addressed [16].

III. Evaluating System Risk

In this work, power systems risk evaluation [10] is considered as a steady state problem, where steady state probabilities are calculated. We have used two methods for calculating the probabilities of outages of system components namely, a state enumeration approach and a Monte Carlo simulation approach.

A. Branch outage transitions

A state-space diagram is built [8], considering the transition between states of the element under study, as is shown in fig. 1 where λ is the failure rate and μ is the repair rate.

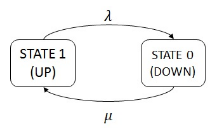

Figure 1: State Space Diagram

We can model the expected time that the element takes to make the transition from state 1 to state 0, as in (3). This is known as the *mean time to failure* (MTTF).

$$E(\mathrm{T}) = \frac{1}{\lambda} \tag{3}$$

Similarly to (3), there is a random variable that goes from state 0 to state 1, according to (4):

$$E(\mathrm{T}) = \frac{1}{\mu} \tag{4}$$

And this is the *mean time to repair* (MTTR).

B. Markov chain and state enumeration

We assume the outage event in each branch can be modelled as a Markov process in which the transition time between a healthy state to a failed state (and vice versa) follows an exponential distribution. We therefore model each branch as a two-state Markov process. Considering that a Markov process [17] can be at a finite or infinite number of states $0, 1, 2, \ldots$, at time t, it is correct to interpret that the status of the process at time t is described by $\mathrm{X}(t)$ and equals the state j that the process has at that moment. Now suppose that the process is in state i at time t_0. The probability that the process goes into the state j at time $t_0 + t$ is given by:

$$P_{ij}(t_0, t) = P\{\mathrm{X}(t_0 + t) = j | \mathrm{X}(t_0) = i\} \tag{5}$$

and this probability is independent of the behaviour of the process $X(t)$ prior to the instant t_0. The transition probability from state i to state j does not depend on the initial moment t_0 but only on the elapsed time between the transitions. So, the (5) reduces to:

$$P_{ij}(t) = P\{X(t_0 + t) = j | X(t_0) = i\} \tag{6}$$

In the case of the single repairable component shown in fig. 1, the steady state probabilities are:

$$\lim_{t\to\infty} P(X(t) = 1 \mid X(0) = i) = p = \frac{\mu}{\mu + \lambda} \tag{7}$$

and

$$\lim_{t\to\infty} P(X(t) = 0 \mid X(0) = i) = q = \frac{\lambda}{\lambda + \mu} \tag{8}$$

These steady state probabilities expressions are applicable irrespective of whether the system starts in the operating state 1 or in the failed state 0. Now we define the vector S to contain all system states when the system is in an N-1 state. That is, $S = 0$ means that all branches are connected, and $S = i$, with $i \in \{1, \dots, N\}$, means that the ith branch is disconnected, but all other branches are connected.

The probability of $S = i$, for $i \neq 0$, is:

$$P(S = i) = q_i \prod_{\substack{m=1 \\ m\neq i}}^{N} p_m \tag{9}$$

and when $i = 0$ (no outage):

$$P(S = 0) = \prod_{m=1}^{N} p_m \tag{10}$$

C. Reliability performance indices

After obtaining the state probabilities and the performance indices for N-1 states, the reliability performance indices are calculated. First, the reliability performance index of thermal violations for each *ith* N-1 scenario is calculated as in:

$$RPI_i = P(S_i) \times PI_i \tag{11}$$

where:

- $P(S_i)$ state probability of *ith* scenario,
- PI_i performance index for thermal violations of *ith* scenario.

Secondly, the reliability voltage performance index is calculated in similar fashion according to:

$$RPIv_i = P(S_i) \times PIv_i \tag{12}$$

where:

- $P(S_i)$ state probability of *ith* scenario,
- PIv_i performance index for thermal violations of *ith* scenario.

Both indices are encircling the severity of a contingency, but observing different variables in the system. The one in (11) observes thermal limit violations, whereas (12) observes bus voltage limits violations. Both of them include the probability of the system of being at certan state S_i and this yields a different ranking compared to the ones obtained by (1) and (2).

Moreover, we obtain the conditional expected value of the performance index via the analytical computation, for both indices, as shown in the next subsection.

D. Performance Index Conditional Expectation: Analytical Computation

The conditional expected value [9] of the performance index is calculated according to (13). This value represents the average value of the performance index over the probability of N-1 branches outages scenarios, including the case of no outage, i.e. $i = 0$.

$$E(PI \mid S_0 \cup S_1 \cdots \cup S_N) = \frac{\sum_{i\in S} PI_i\, P(S_i)}{\sum_{i\in S} P(S_i)} \tag{13}$$

This value is obtained for for thermal and bus voltage violations, respectively. Finally, via Monte Carlo simulation we obtain the state probabilities in order to compare to the results obtained via analytical computation.

E. Monte Carlo simulation

In this section the probabilities for each state are calculated via Monte Carlo simulation [10]. $M = 10{,}000$ samples were drawn. $PI_{i(j)}$ is the performance index value where $i(j)$ is the N-1 state in the *jth* sample. The sample mean of the performance index is calculated with (14):

$$\widehat{PI} = \sum_{j=1}^{M} \frac{PI_{i(j)}}{M} \tag{14}$$

This value, as well as in (13) is obtained for thermal an bus voltage violations, respectively. Lower and upper limits with a 95% level of confidence for the $\widehat{PI}$ are calculated with:

$$\widehat{PI} \pm 1.96 \frac{s}{\sqrt{M}} \tag{15}$$

The sample standard deviation is calculated according to:

$$s = \sqrt{\frac{\sum_{j=1}^{M} (PI_{i(j)} - \widehat{PI})^2}{M - 1}} \tag{16}$$

In the next section, we present the results for the test system we worked with.

IV. Simulation and results

The three area test system shown in fig. 8 is a test system that is based originally from the IEEE Reliability Test System 96 [7]. Lately, changes have been applied to it to be suitable for modern power system analytical needs. This is a task that is under the National Renewable Energy Laboratory supervision. The changes can be consulted in the reference [4]. In this system we only used the normal rates (i.e. thermal limits under normal operation) for each branch included in the data. For determining the value of performance index we use the two approaches: analytical and via simulation. The results are shown in the next two subsections.

A. Performance index for three area system via calculation

In fig. 2 the distribution of the performance index (PI_i) value is shown. In the fig. 3 we show the reliability performance index (RPI_i) distribution.

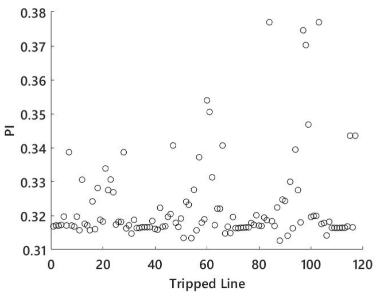

Figure 2: Performance index - Three area system

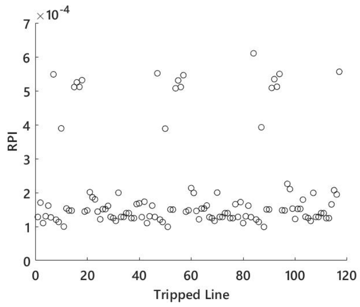

Figure 3: Reliability performance index - Three area system

The conditional expected value obtained using (13) is:

$$E(PI \mid S_0 \cup S_1 \cdots \cup S_N) = 0.3172$$

And for the voltage performance index we have:

$$E(PI \mid S_0 \cup S_1 \cdots \cup S_N) = 0.5860$$

Now, the voltage performance index and its reliability performance index version are shown in fig. 4 and fig. 5.

Even though RPI and RPI_v analyse different violations in the system, they indicate similar critical scenarios to be looked at. fig. 3 And this is because both factor the effect of probability of a contingency to happen. Also, a set of contingencies is indicated by both reliability indices, where classical indices (PI and PI_v) do not identify.

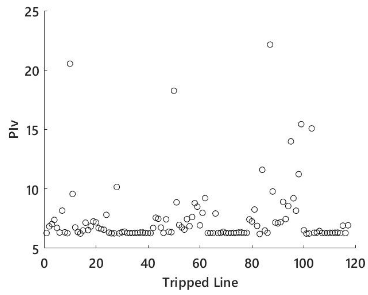

Figure 4: Voltage performance index - Three area system

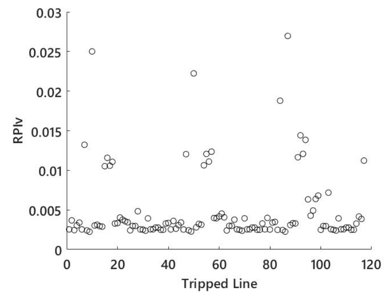

Figure 5: Reliability voltage performance index - Three area system

B. Performance indices for three area system via simulation

In this section, we calculated the probabilities of contingencies using Monte Carlo simulation rather than direct analytical calculations. The advantage of using Monte Carlo simulation is in that we can also derive the distribution of the performance index rather than just a point calculation as it is evident in fig. 6 (thermal limit index) and fig. 7 (voltage limit index).

- $\widehat{PI} = 0.3173$
- confidence bounds were $[0.3172, 0.3174]$

For the voltage performance index we obtained:

- $\widehat{PI_v} = 0.5825$
- confidence bounds were $[0.5726, 0.5924]$

Regarding the type of contingencies, the sample results are shown in table I:

Table I: Types of contingencies

Total samples	**No outage**	**N-1 events**	**N-2 events**	**N-3 events**
10000	9254	713	31	2

The main difference between these two rankings PI_i vs. RPI_i (either if we analyse loadability or voltage violations) relies in that the ranking obtained via RPI_i captures the probability of the contingency to happen. If we look at the probability of outage from branch 84 when it is combined with the severity, i.e. RPI_i, this yields the highest contingency ranking. Whereas if we follow the classical approach of PI_i, the most critical contingency

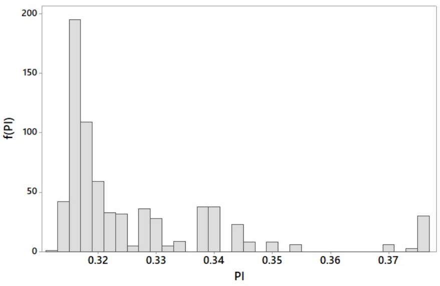

Figure 6: Performance index - Three area system

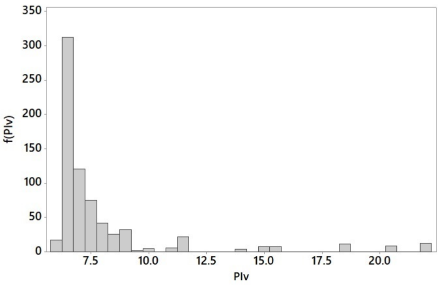

Figure 7: Performance index - Three area system

is when line 103 is out. Also, using the RPI_i ranking we can identify a threshold of contingencies that range in the interval $(0.0005, 0.0006)$, whereas using the PI_i we can see more sparsity.

V. CONCLUSIONS

This potential difference in rankings is important when it comes to analysing the steady state security of the system and therefore a probabilistic approach leads to a more reliable estimation of the system's risk. More work on the performance index for bus voltage violations is expected, since it would yield different rankings compared with the one that assess transmission loadability violations of rates.

Over looking a critical scenario in the bulk power system can happen; and this is because of the size of the system. Implementing these subroutines in real time with a time step of minutes is beneficial to the operator and the whole crew in the control room. More realistic decisions can be made based on the severity of the contingency and also the probability to happen rather than a deterministic approach.

We can use this method for other systems as well since the IEEE RTS system we used in this paper is essentially a connection of three identical smaller systems.

With the entry of a large surge of renewable generation to be expected in the future, it is necessary to determine new control variables different from loadability and voltage violations. Since the generation fleet is expected to be flexible (synchronising and desynchronising) thrhough the day, inertia is changing with it too. This variable can be looked at if a disturbance happens in the system, following a similar approach as shown in this paper. Moreover, it is interesting to perform this task via time based simulation, since the constant changing conditions (load and renewable energy injections) of the system will also change the distribution of both rankings.

REFERENCES

[1] National Grid, *System Operability Framework 2016*, National Grid Transmission System Operator, November 2016.

[2] Off shore wind electricity. [Online]. Available: https://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/offshore-wind-energy/

[3] J. Cochran, M. Miller, O. Zinaman, M. Milligan, D. Arent, B. Palmintier, M. O´Malley, S. Mueller, E. Lannoye, A. Tuohy, B. Kujala, H. Holttinen, J. K. M. Sommer, and S. Soonee, "Flexibility in 21st Century Power Systems," *21st Century Power*, May 2014.

[4] GRID Modernization Laboratory Consortium - US Department of Energy, *GMLC*, 2017.

[5] Xi-Fang Wang and Yonghua Song and Malcolm Irving, *Modern Power System Analysis*. Springer, 2008.

[6] P. Kundur, *Power System Stability and Control*. McGRaw-Hill, 1993.

[7] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee," *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 1010–1020, Aug 1999.

[8] Roy Billinton and Ronald N. Allan, *Reliability Evaluation of Engineering Systems*. Springer, 1992.

[9] Athanasios Papoulis and S. Unnikrishna Pillai, *Probability, Random Variables and Stochastic Processes*. McGraw Hill Series in Electrical and Computer Engineering, 2002.

[10] Wenyuan Li, *Risk Assessment of Power Systems*. IEEE Press-Wiley, 2014.

[11] Ebrahim Vaahedi, *Practical Power System Operation*. IEEE Press-Wiley, 2014.

[12] W. S. Tan and M. Shaaban, "Ranking of power system contingencies based on a risk quantification criterion," in *2015 IEEE Student Conference on Research and Development (SCOReD)*, Dec 2015, pp. 356–361.

[13] J. McCalley, S. Asgarpoor, L. Bertling, R. Billinton, H. Chao, J. Chen, J. Endrenyi, R. Fletcher, A. Ford, C. Grigg, G. Hamoud, D. Logan, A. P. Meliopoulos, M. Ni, N. Rau, L. Salvaderi, M. Schilling, Y. Schlumberger, A. Schneider, and C. Singh, "Probabilistic security assessment for power system operations," in *IEEE Power Engineering Society General Meeting, 2004.*, June 2004, pp. 212–220 Vol.1.

[14] S. Meliopoulos, D. Taylor, C. Singh, F. Yang, S. W. Kang, and G. Stefopoulos, *Comprehensive Power System Reliability Assessment Final Project report*, Power Systems Engineering Research Center, 2005.

[15] U.G. Knight, *Power Systems in Emergencies*. John Wiley and Sons LTD, 2001.

[16] Comisión Reguladora de Energía, *Código de Red*, CENACE, 2016.

[17] Geoffrey Grimmett and David Stirzaker, *Probability and Random Processes*. OXFORD University Press, 2001.

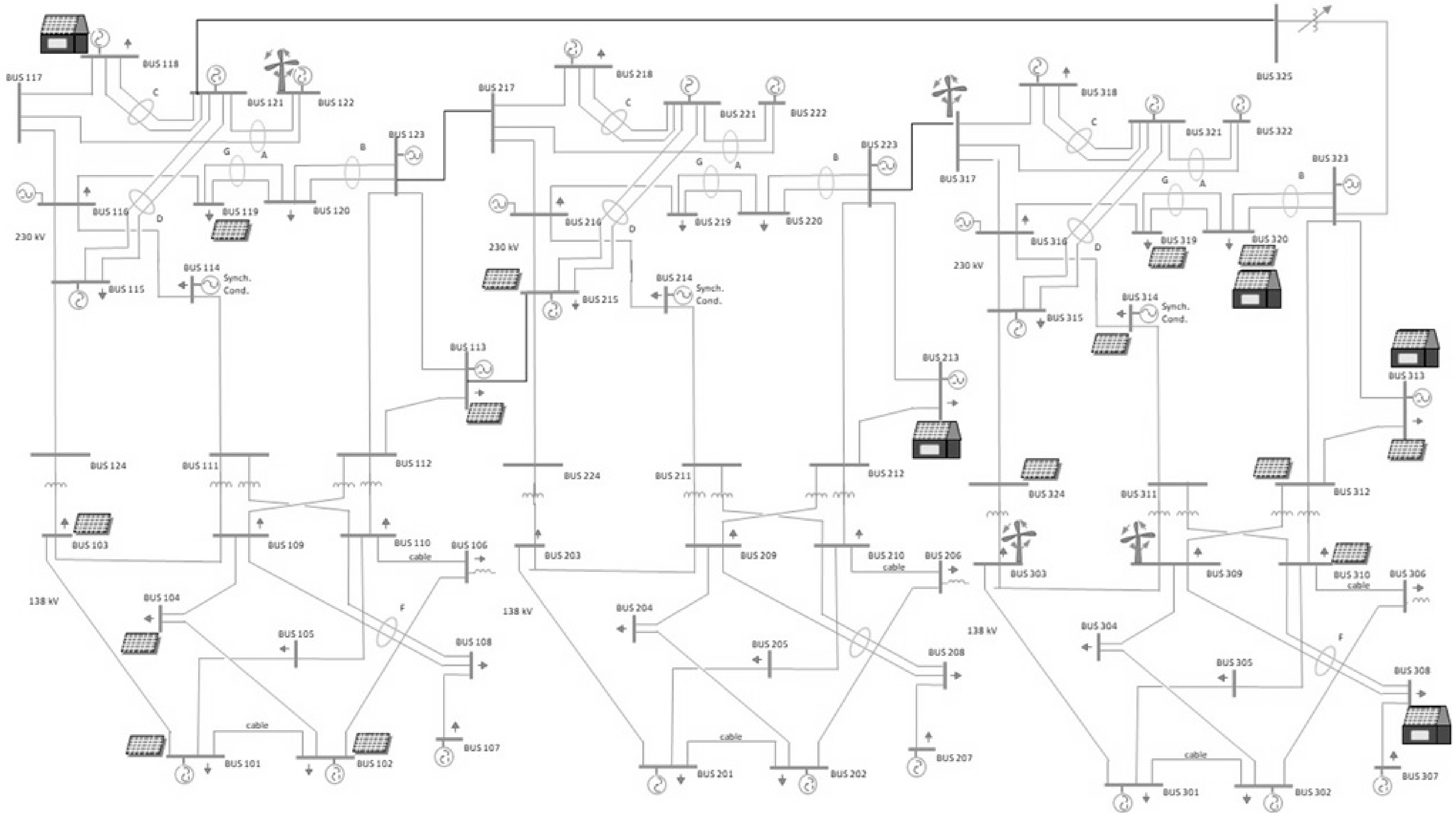

Figure 8: Three area 73 bus system [4]