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EXTENDED OPA MODEL FOR CASCADING FAILURE ANALYZES

Aleksandra Kanevce
Faculty of Computer Science and Engineering, University Ss. Cyril and Methodius
Skopje, Macedonia

Igor Mishkovski
Faculty of Computer Science and Engineering, University Ss. Cyril and Methodius
Skopje, Macedonia

Ljupco Kocarev
Faculty of Computer Science and Engineering, University Ss. Cyril and Methodius
Skopje, Macedonia

ABSTRACT

In this paper the reliability of networks and especially the cascading failures are analyzed. As a special type of network the electric power grid is considered. The network is modeled (taking into account the nature of electricity networks) using linear programming dispatch of the generated electricity to the consumers. The data of the electric power system of Southeast Europe are used. The reliability of the network is analyzed using the OPA model which enables cascading failure analyzes based on probabilistic outages of the overloaded lines and includes long-term upgrading of the system in response to the increased electricity demand over the time. In this paper, the OPA model is extended to include the minimum generation capacity of each power plant and it is analyzed how this constraint affects the cascading failures.

The results show that this constraint introduces additional instability in the system that leads to higher cascading failures of the power transmission lines.

I. INTRODUCTION

Cascading failure is considered to be a sequence of certain dependent components failure that causes weakness of the system [1]. The analysis of the cascading failures is complex, in terms of how these failures depend on each other and how the damage can be minimized when there is a cascading failure. For precise and realistic examination of the damage caused by the cascading failure it is necessary to examine all possible combination of different number of outaged lines, which is very time and processor intensive and therefore it is not commonly used.

In the case of electric power system the damage caused by the cascading failure is called blackout. The size of the blackout depends on the number of outaged lines and the importance of these lines in the power grid. In addition, when there is blackout the consumers remain without electricity which has a very high cost. Therefore, analyzing the vulnerability of networks, in terms of cascading failure is very important and motivates research ad practice on modeling the dynamical evolution of the power grid maintaining power system reliability.

Because analysis of cascading failures, by examining all the possible combinations is a complex process, various simplified models are developed for this purpose. One of them is the OPA model [2, 3, 4, 13] that uses certain probability of an initial disturbance in the system. Furthermore, a cascade occurs so that each line that is in a critical condition (runs on 1% of its maximum capacity) is given certain probability of failure. The linear problem of power dispatch is solved, until there are new outaged lines, also including the previously outaged lines. In fact, the OPA model includes in the cascade only those lines that are most likely to outage due to their overload. On the other hand, the OPA model is considering the system in a long term and it properly performs system upgrade due to increased electricity demand. As the load increases, the average blackout size increases very slowly, until, at a loading called the critical loading, there is a sharp change and average blackout size starts increasing much more quickly. Evidence for a critical loading is presented in power system models that represent some cascading failure mechanisms [10, 11, 12]. From this perspective, one can also analyze the development of the system in a given time period, i.e. the state of equilibrium of the system can be determined in which the growing electricity demand will be adequately served by the upgraded capacity of the network – in terms of production capacity and transmission lines capacity, and taking into account the corresponding probability of cascading failure in that system.

In this paper we use the OPA model to analyze Southeast European power transmission system and we have modified the OPA model to include one very important characteristic of the electric power systems, which contributes to higher cascading failures.

The data for the electric power system of the Southeast Europe are used as a whole system and not as separate electric power systems. According to the agreements that are already signed as the Energy Community Treaty [5] and Southeast Europe Regional Electricity Market (SEE REM) [6] and South-East Europe Cooperative Initiative [7], the Southeast Europe should have a single trade for electricity in the future. In many papers the electric power system of the Southeast Europe is analyzed as a whole system [6, 7, 8, 9].

This is the outline of the paper. In the second section the model of the power transmission network is presented, as well as the data used for modelling the electric power transmission system of Southeast Europe. In the third section a short description of the OPA model is given. The forth section presents the extension to the OPA model. The obtained results are presented in the fifth section.

II. MODEL OF THE POWER TRANSMISSION NETWORK

The electric power transmission network of the Southeast Europe is modelled as a graph with n nodes interconnected by m edges or transmission lines. Each transmission line j connects two nodes and has a power flow, denoted as p_j. The power flow can be positive or negative, which defines the direction of the power flow. Each line is also characterized by the maximum power flow it can carry P_j^{max} , which implies $p_j < P_j^{max}$, and the transmission cost of the line j, denoted as z_j. The network nodes represent electricity consumers or electricity generators. To use the standard network flow model we have transformed the generation nodes. The transformation is used in order to associate cost and capacity for each generator. This is done by replacing each of the generation nodes with a pair of nodes with an edge connecting them [14, 15]. This edge is characterized by the parameters of the generator, such as generation cost, maximum and minimum electricity production. Generator *i* produces power g_i, measured in MW. Each generator has an installed capacity or the maximum power available for generator *i*, denoted as G_i^{max}.

The power generation cost of a specific electricity generator is an average of the prices of this type of power plant in certain region. The cost mainly depends on the type of the power plant *i* and is denoted as c_i, measured in EUR/MWh.

The electricity demand at node *i* is denoted as d_i. There has to be balance at each node, or the total power flowing into the node minus the total power flowing out of the node must be equal to the corresponding consumption or generation (depending on the type of the node). The power balance can be expressed as:

$$A \cdot p = \begin{bmatrix} -g \\ d \end{bmatrix} \tag{1}$$

where generators are attached to the first *k* nodes, and electrical loads are connected to the nodes *k + 1,..., n*. Matrix $A \epsilon R^{n\,x\,m}$ is the node-incidence matrix of the graph.

The objective function of this linear programming problem is:

$$\text{minimize} : \sum_{i=1}^{k} c_i g_i + \sum_{j=1}^{m} z_j \left| p_j \right| \tag{2}$$

which is subject to the constraints $|p_j| \leq P_j^{max}$ for *j=1,2,...,m* and $g_j \leq G_i^{max}$ for *i=1,2,...,k*.

A. Linear programming power redispatch

There are situations when the power cannot be properly transferred through the network or the network brakes into multiple islands and this happens when one or more of the lines are overloaded or outaged. In these situations there is no solution for the linear programming problem. In order to satisfy the above constraints and obtain a solution in these cases it is necessary to shed load or to redispatch the power [10]. The loss or shed of load is defined as the sum of the differences of the required and the obtained power in each node.

For this purpose, it is necessary to add one more term in (2), i.e. in the objective function, in order to minimize the load shed or to maximize the electricity dispatched to the consumers:

$$-W \cdot \sum_{i=k+1}^{n} (l_i) \tag{3}$$

where *W* is a price for the load shed and it is set to 100. The minus sign is because the objective function is to minimize the cost and here we need to maximize the electricity load.

The following constraint should also be added to the system:

$$0 \leq l_i \leq l_i^{nom} \quad \mathit{for}\ i = k+1, \ldots, n \tag{4}$$

The constraint given in (4) shows that the obtained load cannot be greater than the required consumption.

B. Parameters used in the model

In this paper the power transmission network of Southeast Europe is used, which includes the following countries: Macedonia, Serbia, Bulgaria, Albania, Kosovo, Croatia, Bosnia and Herzegovina, Montenegro, Slovenia, Greece and Romania. We are considering power transmission lines of 440kV and upper voltage levels. The power grid of European network of transmission system operators for electricity (ENTSO) is used [16]. Figure 1 shows the power grid of Southeast Europe.

The nodes of the model represent the transformers and the generation capacities. Each generator is connected to the nearest transformer (node) in the network. The electricity generation cost mainly depends on the type of fuel and Table 1 provides the electricity generation costs for each type of power plant, measured in EUR/MWh.

There is also information about the installed capacity for each of the generators.

The initial electricity consumption in each node is calculated according to the total consumption in that country (this data is provided in [6, 16, 17]) and the density of population connected to each node (this data is provided in [18]).

Figure 1. Electric power grid of Southeast Europe

Table 1: Electricity generation prices

Power plant	EUR/MWh
Coal fired thermal power plant	40
Heavy fuel oil thermal power plant	80
Natural gas thermal power plant	68
Hydro power plant	60
Combined heat and power plant	58
Nuclear power plant	55
Import	70

III. OPA MODEL

In this paper, as a basis for modelling the evolving grid and the cascade failures, the OPA model is used [2]. Also, we use the direct response strategy for upgrading the system. This policy directly responses to the cascading failures so that the capacity of each line that was outaged in the previous step and was involved in load shedding is upgraded by multiplying the line capacity by a constant factor.

The OPA model uses two time scales. Over the slow time scale the grid is evolving, or the power demand is slowly increasing. In response to this increased power demand, the network is upgraded in terms of transmission lines capacities and electricity generation. On the other hand, over the fast time scale, the power is dispatched through the network, or the linear programming problem is solved.

Over the slow time scale, at the beginning the average load is increased. After that, the corresponding policy is applied. Each line that is outaged in the previous time step in which there was load shedding is upgraded by a factor μ. Next, there is initial disturbance at each time step, or each line is outaged with probability p_0. Taking this into account, the linear programming problem is solved and the loss of load is calculated. Using the results, the overloaded lines are detached. These lines are the most critical when there is cascading failures. Each of these lines is outaged with probability p_1. The linear programming model is solved while there are new outaged lines and the information for the load shed is calculated. If there are no more lines outaged, the generation is upgraded. This generation upgrade represents power plant upgrade or addition of new generators. After that the process starts all over again by increasing the average consumption.

IV. EXTENDED OPA MODEL

One of the main characteristics of the electric power grids is that in each moment the electricity generation must be equal to the electricity load. The fulfillment of this condition is complicated by the nature of the power plants. Namely, each power plant has a maximum generation capacity, but from purely technological reasons, power plants cannot also operate under a certain power that depends on the type of the power plant. If a particular plant is needed to produce less electricity than its minimum, then it would be needed to turn off the power plant and to provide electricity from other sources. But the process of turning off and on a thermal power plant is usually long and expensive and is not performed on a daily basis. Therefore, there should be a long term plan of how plants will be included or excluded in the system in certain parts of the year. But, despite this, there are situations where the minimum electricity generation is still greater than the demand for electricity. In these cases the surplus must be exported, which includes additional load of the system.

This minimum electricity generation is added to the OPA model and one more constraint is added in the linear programming problem:

$$G_i^{\min} \le g_i \qquad (5)$$

In (5) the G_j^{min} vector is calculated so that the minimum generation capacity of each thermal power plant is 60% of its maximum generation capacity, and the minimum generation capacity of each hydropower plant is 20% of its maximum generation capacity. This vector is recalculated in each time step according to the generation capacity upgrade.

In each time step the minimum generation capacity is compared to the electricity demand. If the minimum production is higher than the demand, this difference is uniquely divided among the neighbouring nodes outside of the region, as their electricity demand. In reality, this corresponds to the export of electricity outside the region.

V. RESULTS

In this paper, we are analyzing the difference in the stability of the system with adding the minimum generation capacity of each power plant.

One of the measures of the stability of the system is analyzing the load shedding. In fact, that is the difference between the electricity demand and the actual dispatched electricity to the consumption nodes or that is the energy unserved. Fractional load shed is the sum of the load shed in one time step divided by the total power demand in that step. In Fig. 2 the fractional load shed is shown for the electric power system of Southeast Europe when there is no minimum generation capacity or the minimum generation capacity of each power plant is zero, i.e. if there is no need of a certain power plant it will be turned off on a daily basis. In Fig. 3 the fractional load shed is presented for the case where the power plant cannot be turned off on a daily bases and each plant has a minimum generation capacity that has to be produced. The difference between the two plots can be noticed and it can be concluded that there is more power shed when there is the minimum generation capacity included. This difference can be, also, noticed on Fig. 4 where the log-log plot of the probability of exceedance is presented. In fact, the complementary cumulative distribution function of the fractional load shed is given for the two analyzed cases. The probability of higher load shed in the case with added minimum generation capacity is much higher than in the other case. Effectively, the probability for a higher value of the fractional load shed than 0.004 is 3.1% in the case with minimum generation capacity and it is 2.2% for the case without minimum generation capacity.

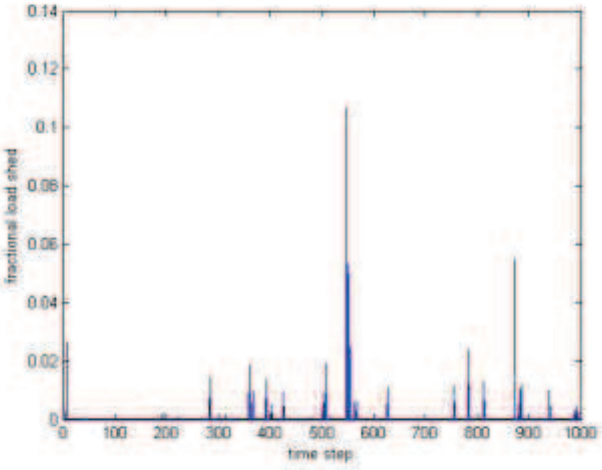

Figure 2. Fractional load shed in the case without minimum generation capacity

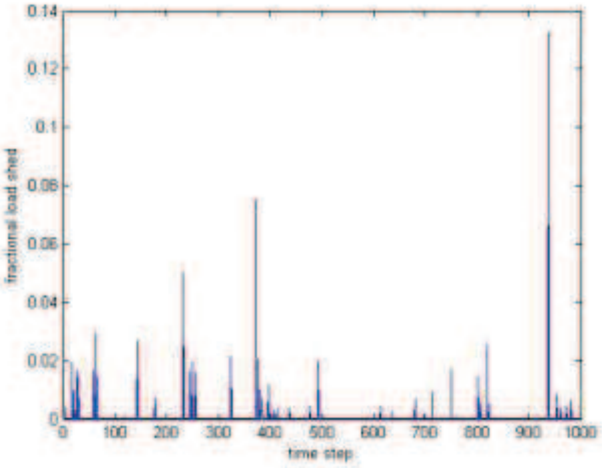

Figure 3. Fractional load shed in the case with minimum generation capacity

It is obvious that the addition of this constraint introduces instability in the system. This instability is caused by the more power that needs to be redispatched (implied by the minimum generation power of each plant). This is, normally, followed by higher line loading and according to that there is much higher probability for the lines to be overloaded. This leads to more cascading line outages as a consequence of the higher probability of outaging overloaded line. On Fig. 5 the fractional line loading is presented for the two analysed cases. It is clear that in the case where there is a minimum generation capacity the lines are more loaded than in the other case.

This leads to more cascading transmission lines failures, and that means to larger blackouts. The histogram of the number of lines outaged in each cascade failure or the cascade size is presented in Fig. 6. Again, it is confirmed that the addition of the minimum generation power of each power plant contributes to larger cascading outages of the lines.

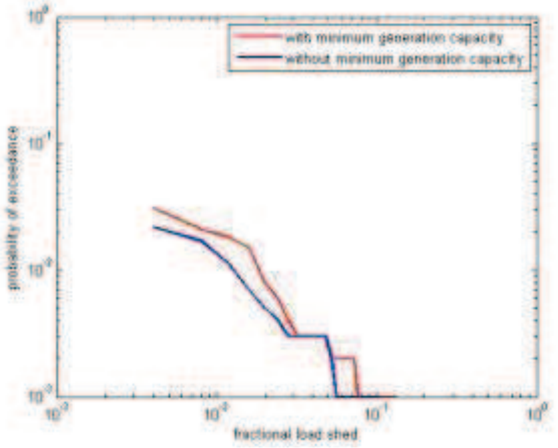

Figure 4. The probability of exceedance of the fractional load shed in the two analyzed cases

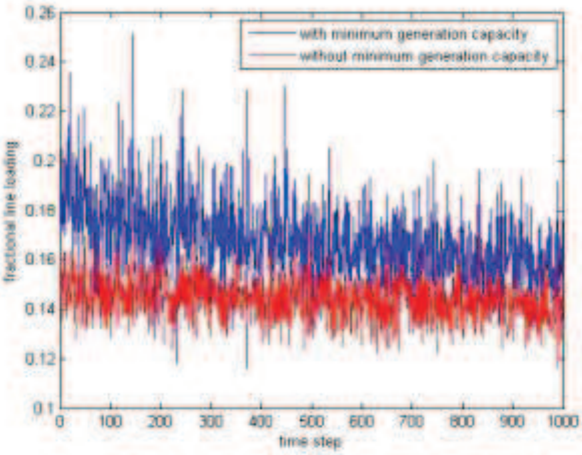

Figure 5. The fractional line loading in the two analyzed cases

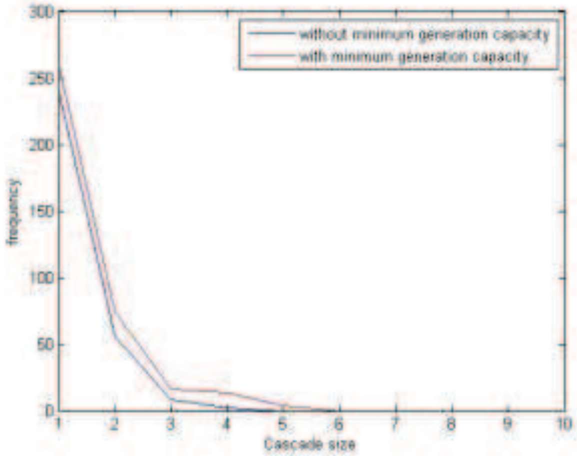

Figure 6. Histogram of the cascade size in the two analyzed cases

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