Impact of Remote Control Failure on Power System Restoration Time

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Abstract—Extended blackouts are rare events but when they occur they cause severe stress on the society. After a blackout it is important to have a efficient restoration strategy and to be aware of the risks that could extend the restoration process. One important risk during the restoration process after a blackout is the dependence of limited back up power at substations. The back up power is needed to control circuit breakers and for communication equipment. If the outage time is extensive the back up power might run out and the ability to control the circuit breakers is lost and this will extend the restoration time even further. In this paper a stochastic model of the restoration process of a power system with several substations with an uncertain backup power is presented. The model uses a Monte Carlo simulation to identify the impact of remote control failure on power system restoration time.

I. INTRODUCTION

Large and extensive blackouts are rare events that have a huge impact and cause severe stress on the society. Even though much effort is taken to avoid them they occur from time to time. The restoration process after a blackout is a complex and time consuming task. The time it takes to restore the system is critical since the local battery back up at the substations are limited. If the local battery backup runs out the ability for remote control is lost and the circuit breakers has to be switched manually. A manual operation of circuit breakers is much more time consuming than a remote control and will hence extend the outage time. The local backup time at substations is also uncertain due to age effects. If the local battery back up runs out at several substations there might be a problem with the availability of personal with the right knowledge of how to execute a manual switch. It is hence of interest to describe the current situation regarding the local backup power at the substations and the resources available for manual operation of switchers. The restoration time and the restoration sequence also depends on the operator. If the operator is experienced the time it takes to take decision during the restoration process might be less then for a novice operator. Analysis and discussions of the power system restoration process is given in [1],[3],[5],[6] and [7]. In [8] has the consequences of a loss of power supply in the substation been discussed and identified as a risk that could delay the restoration process. The local power supply has also been discussed in [2] as a risk that could delay the restoration process and hence extend the outage time. If the restoration

time is too long then there is a risk that some substations can not be remotely controlled because of the lack of local back up power which will lead to very long restoration time. The aim of this paper is identify the impact of remote control failure on power system restoration time. In section II the pre-process is defined and a description is given. In section III the main process is described. In section IV a description of how the structure of the power system and the restoration path is modeled using graph theory is given. Section V describes the Monte Carlo simulation. In section VI conclusions are given.

II. PRE-PROCESS

The restoration process after a black out can be divided into two processes, the pre-process and the main restoration process. The-pre restoration process deals with the activities that takes place directly after a black out and occurs only ones. The events between the black out and the first stable node is defined as the pre-restoration process. Directly after a black out a strategy is to open all circuit breakers (CB) within the main network and all CB between the main network and subnetworks automatically. This strategy is known as the all open strategy [1]. Its advantage is that the status of the CB is well defined. A different strategy is to open only selected CB's, this strategy is known as controlled operation strategy [2] and [6]. The strategy used here is the all open strategy. It is also assumed that there can not be any failure in the CB when opened. All remote communication with the substations are now depended on the local back up power. After a sudden blackout the first thing an operator responsible for the restoration has to do is to get an overview of the situation and decide to perform a black start of the power system. It is reasonable to assume that the time between the blackout and the decision to perform a black start is stochastic since each blackout is unique and different operators have different experience and ability to take decisions. When the decision is made to perform a black start an operator has to order a black start of the first generator. The time it takes to execute a black start of the first generator is assumed to be stochastic since this is done manually. When the black start is executed on the first generator, load has to be given

to create a stable system to continue the restoration process on. This is done by closing a circuit breaker to a subnetwork to get load or by letting a second generator consume power. The time it takes to create a stable system to continue the restoration process from is assumed to be stochastic since this is done manually. All the stochastic times are assumed to have a Weibull distribution with a mean value that depends on the operator. The experience or how fast a certain operator is, is hence a stochastic variable. The probability density function for times with a Weibull distribution that depends on the operator is modeled as

$$f_{T_i} = \frac{k_i}{\lambda_i(e_o)} \left(\frac{t}{\lambda_i(e_o)} \right)^{k_i-1} e^{-\left(\frac{t}{\lambda_i(e_o)} \right)^{k_i}} \quad (1)$$

where e_o represents the experience of the operator and is assumed to be Weibull distributed where the scale parameter is set to 1 and

$$\lambda_i(e_o) = \lambda_{0i} e_o \quad (2)$$

where λ_0 is the nominal value of expected time. The time for the pre-restoration process is

$$T_P = T_1(e_o) + T_2(e_o) + T_3(e_o) \quad (3)$$

where T_1 is the stochastic time for an operator to get an overview of the situation, T_2 is the stochastic time for dead start of the first generator and T_3 is the stochastic time for stabilizing the first connected node.

III. MAIN RESTORATION PROCESS

When the first node is connected to the black start unit and load is given the restoration of the rest of the system can be started. This is done by connecting nodes by operating CB's, stabilizing by connecting load in the nodes and by matching generation with load. The flow chart describing the restoration process is shown in figure 2. The first step is to find a suitable node to connect and to operate CB's towards this node, A in the flow chart. If there is no backup power a remote control of the CB's is not possible and a manual closure of the line has to be executed, B and E. The next step is to connect load to the new node, C in the flow chart, this is done by operating CB's towards a subnetwork. If there is no backup power at the subnetwork node a remote control of the CB's is not possible and a manual closure of the line is needed, B and E in the flow chart. The last step is to match production and consumption, D, before closing to a new node again. Below the different steps will be described in detail.

A. Connect to a new node

The operator has to choose which new node to energize, hence the restoration path is depended on the operator. The restoration path is in this paper modeled as a uniform random process where each path has the same probability. A more detailed description is given in the next section. The decision and execution time for choosing and closing a CB is assumed to depend on the operator. An experienced and skilled operator can take quick decisions while a novice and unskilled operator needs more time to take a decision. This stochastic time is

denoted T_A and its probability density function is given by equation 1.

B. Remote control

If there exists backup power at the substation the closing of CB's at the substation can be remote controlled. If the backup power at the substation has run out a team has to be sent out for a manual closure of CB's.

C. Connect to a subnetwork

When a new node is connected, load has to be given to avoid over voltage. The operator for the main network has to find and call an operator at the subnetwork and ask for load. The operator for the subnetwork is then closing a line towards the main network by operating CB's. The time it takes to find and call a suitable operator at the subnetwork and the execution time for closing a line to the main network if there exists power at the node in the subnetwork depends on the operator according to equation 1. This stochastic time is denoted T_C . If there is no local back up power at the substation a manual closure of the CB has to be executed.

D. Matching production and consumption

Before closing to a new node the operator has to match generation and consumption. The operator has to find and call a suitable producer and ask for generation capacity for a new node. The time it takes to find a suitable producer and to make an agreement with the producer is depended on the operator according to equation 1. This stochastic time is denoted T_D .

E. Manual closure

If the back up power has run out a team has to be sent for a manual operation of CB's at the substation. The time it takes to find a team and the time it takes for the team to reach the substation and execute a manual operation of CB's is assumed to be stochastic since the availability of personal with the right experience, traffic and the condition on the roads are unknown. The time it takes for a team to execute a manual closure of CB's is denoted T_E .

F. Main network restored?

If the main network is not intact the operator has to do the same thing all over again.

G. Subnetwork restored?

If the main network is intact the operator has just no continue to match production with load until all subnetworks in the system are connected.

The main restoration time, T_M , is the sum of all actions need to restore the system, hence $T_M(T_A, T_C, T_D, T_E)$. The total restoration time is given by

$$T_{RT} = T_P + T_M \quad (4)$$

Fig. 1. The main restoration process

IV. POWER SYSTEM DESCRIPTION USING EDGE NODE MATRIX

A power system consists of substations connected to each other and each substation can have several connections to other substations in the main network see figure 2. A way of describing the structure in a power system is to use a edge node matrix. For a profound theory in graph theory see [4]. The structure of the power system as a function of the status of the CB using graph theory is given by

$$A = (A_0^T C)^T \quad (5)$$

where A_0 is an edge node matrix representing a full system and C is a diagonal matrix representing the status for the CB's, 1 when the nodes is connected and 0 when two nodes are disconnected. Each substation which is not connected to the restored grid gets its power from a local power source. A way of describing whether a substation is in contact with the main grid or not and runs on back up power can be expressed by

$$B = (A^T A)^n \quad (6)$$

where element w_{ij} in the B matrix is a none zero element if node i and node j has a n^{th} order connection or less. If a black start unit is connected to node i all nodes j with a zero element in the raw vector V_i from the B matrix are running on backup power. Lines that can be used to energize nodes with a first order connection to the restored network is found by

$$D = (A_0 - A)V_i^T \quad (7)$$

where all the none zero elements in the vector D represents lines with a first order connection to the restored system. A vector E is introduced to describe the probability to close line k . The elements in vector E is given by

$$E_k = \begin{cases} 1 & D_k > 0 \\ 0 & D_k = 0 \end{cases} \quad (8)$$

and the probability to choose to close line k is given by

$$P(X = k) = \frac{E_k}{\sum_{k=1}^M E_k} \quad (9)$$

where M is the total number of lines to choose between. All lines with a first order connection to the restored system is here assumed to be equal important.

Fig. 2. A graph of a network where each node represents a substation and each line represent a transmission line. Node 1 to 6 represents the main network and node 7 to 12 represents substations at subnetwork level

V. MONTE CARLO SIMULATION

A Monte Carlo simulation will be used to find a discrete probability mass function for different initial conditions. The Monte Carlo simulation is performed according to figure 3. N in figure 3 refers to the total number of simulations performed for each case. The restoration process will be performed on a system shown in figure 2. The system is chosen since it is small but still contains several restoration paths. The edge node matrix A_0 is given by a matrix with 12 columns and 13 rows where each row represent a line connecting two nodes. The shape parameter for all Weibull distributions in this case study is assumed to be 4, hence

$$k_i = 4 \quad (10)$$

Fig. 3. The set up structure for the Monte Carlo simulation.

Three different cases will be simulated. One with long local back up time at the main and sub network stations and short time for manual closure of CB's, one case with short local battery back up time at the main and sub network stations and with short time for manual closure of CB's and the last case with short local backup time at all substations and long time for a manual closure. The nominal scale parameters for the Weibull distribution are assumed to be

$$\begin{aligned} \lambda_{e0} &= 1 \\ \lambda_{01} &= 10 \\ \lambda_{02} &= 30 \end{aligned}$$

$$\begin{aligned} \lambda_{03} &= 10 \\ \lambda_{0A} &= 5 \\ \lambda_{0B} &= 5 \\ \lambda_{0C} &= 5 \\ \lambda_{0D} &= 5 \end{aligned}$$

where λ_{e0} is the scale parameter for the experience constant for an operator, λ_{01} , λ_{02} and λ_{03} are the nominal scale parameter for the time T_1 , T_2 and T_3 in the pre-process, λ_{0A} is the nominal scale parameter for the time to choose a restoration path, λ_{0B} is the nominal scale parameter for the time to execute a remote control, λ_{0C} is the nominal scale parameter for the time to connect a subnetwork and λ_{0D} is the nominal scale parameter for the time to match generation and consumption. A Monte Carlo simulation is performed for each case to find the probability density function, the expected restoration time and the variance.

Fig. 4. The Weibull distribution for the time an operator needs to get an overview of the situation after a sudden blackout.

A. CASE 1

In this case there is a long local back up time at the main and sub network stations and short time for manual closure of CB's. The parameters for case one is set to be

Scale parameter	Value [min]
λ_M	60
λ_{BM}	600
λ_{BS}	500

where λ_M is the scale parameter for the time a restoration team needs to reach a substation and execute a manual closure of CB's, λ_{BM} is the scale parameter for the back up time at a main network station and λ_{BS} is the scale parameter for the back up time at a subnetwork station.

B. CASE 2

In this case there is a short local back up time at the main and sub network stations and short time for manual closure of

CB's. The parameters for case one is set to be

Scale parameter	Value [min]
λ_M	60
λ_{BM}	200
λ_{BS}	100

C. CASE 3

In this case there is a short local back up time at the main and sub network stations and long time for manual closure of CB's. The parameters for case one is set to be

Scale parameter	Value [min]
λ_M	120
λ_{BM}	200
λ_{BS}	100

The discrete probability mass function f_{RT} for the restoration time is found from a Monte Carlo simulation for the three different cases and is showed in figure 4. The expected time and the variance found from the Monte Carlo simulation is shown below

Case	$E(X)$	$V(X)$
1	1.89	0.278
2	2.52	0.752
3	3.34	2.17

Case 2 and case 3 visualize the impact of how fast the restoration team can reach a substation for a manual closure. Even though case 2 and case 3 has the same back up time in the system the variance in the restoration time is very different. Case 1 is showed to have sufficient back up time for a restoration process with a low probability of losing ability to remote control CB's. The percentage of nodes in the Monte Carlo simulation that has been connected to the restored network with a manual closure of CB's is shown below.

Case	Percentage of nodes connected manually
1	1.02
2	13.5
3	13.6

The percentage of nodes connected with a manual operation of CB's in case 1 are lower than case 2 and case 3. In case 1 almost all nodes in every scenario are connected with a remote control of CB's and remote control failure are relatively rare events. Case 2 and case 3 have too little back up power in the system and the restoration time strongly depends on how fast a restoration team can reach and execute a manual operation of CB's.

Figure 5 shows the probability mass function for the restoration time. Case 2 and case 3 shows the impact of remote control failure on the restoration time when the nodes in the system has insufficient back up power.

VI. CONCLUSION

In this paper a stochastic model for finding the discrete probability mass function for the restoration time with different initial condition in the power system has been developed. The model is used to study the impact of failure in remote control

Fig. 5. The discrete probability mass function f_{RT} for the restoration time for three cases. Case 1 is marked with x, case two is marked with circles and case three is marked with squares.

on power system restoration time. The impact of failure in remote control on power system restoration time depends on the total back up power in the system in combination with how fast a restoration team can reach and execute a manual operation. In this model sufficient back up power can reduce the restoration time with several hours. Teams with ability to perform a quick manual closure of CB's becomes important when the back up power is insufficient or the restoration outage time is delayed for some reason.

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