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Identification of Transmission Line Capacity in Power System Network Operation

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Abstract. Recently, the consumption of electrical power has gained continuous increase and the option of constructing generation sites at every location of power demand is no longer viable. To augment for this increase, transmission lines are now being required to transfer more power from existing generation sites to consumers. Thus, an increase in the tendency of outage occurrences and other system failures of these transmission lines. This paper focuses on the identification of transmission line capacity in the operation of power system networks. Such that a mathematical model developed and executed on a MATLAB simulation to demonstrate the determination of unutilised capacity in transmission lines network. In order to identify the available capacity, transmission line switching (TLS) power flow operation is implemented on a PowerWorld Simulator. The TLS is on a N-1 security criterion basis of sequential removal from the network of each transmission line. The operating capacity of each transmission line is then obtained by comparing the quantity of power flow to the installed capacity on the line. This comparism leads to determination of maximum amount of power flow through any transmission lines network without the occurrence of outage overload scenarios as well as provide a capability to troubleshoot power system network for any specific line overload.

Keywords: Transmission line capacity; Line switching; PowerWorld simulator; Power system network operation

Introduction

In electric power systems, understanding of transmission line capacity is of importance in network operation. Transmission lines play major role in the transfer of power from generation sites to consumption points (Glover, 2008). Studies have shown that due to insufficient capacity in some transmission lines, the network often undergoes restricted access in transmitting power. However, environmental constraints and right of way (ROW) logistics hinder expansion and construction of more transmission lines. Hence, a recourse to adequate use of the existing capacity on the transmission lines (Overbye, 2008). To execute this adequate usage, a number of determinant real and reactive power flows are usually monitored by power system operators along with voltage levels, network topology, tie-line flows, as well as external transactions and internal bus loads. These quantities are monitored to ensure that they remain within acceptable limits of the existing network or any of the possible post-contingency degradation (Ilić et al., 1998). Network transmission capacity is affected by certain changes in the operation of the power system, whether sudden or gradual. An increase in the overall system load may severely limit additional deliveries of power flow through a particular set of lines. This is because the total deliverable incremental load is now reduced, the overall system capacity may decrease. The loss of a transmission line, which can decrease the maximum load deliverable to some parts of the system while actually raising the capacity of the load supply elsewhere in the network, is an example of such a case (Ilić et al., 1998). Transmission line switching is a system used for a variety of purposes to take lines in and out of the power network, such as to optimize the economic efficiency of generation dispatch and to alleviate conditions of network contingency. Repairs to damaged system modules, load shedding, reduction of outages due to line overloads and loss minimization have also been performed as a line switching technique (Bakirtzis & Meliopoulos, 1987). For further projections into insecurity which could occur on the transmission lines, line switching is used. As loads differ, the transmission lines and entire network becomes more prone to instability resulting in power flow security threat. Transmission line switching essentially affects the configuration of the transmission network and this has a net impact on the transfer of power flow through other transmission lines in the same network.

In this paper, PowerWorld Simulator is used as a simulation tool to execute power flow in a network and thereafter perform analytical representation of selected lines that were switched in the network. Switching of lines redirect part of the flows that could cause overloading of some lines and damage to the network operation through lines with available capacity. The Power World Simulator is also used as a contingency evaluation tool to estimate active and reactive power flows, operating capacity and installed capacity.

In the past, transmission line operators try to find lines with ample idle ability to handle the delivery of power during an interruption or some other contingency due to increased power demand. However, in the identification of transmission capacity for line power flow, many techniques such as load shedding, network reconfiguration, the use of phasor measurement units (PMUs), state estimation (SE) and Benders decomposition have been suggested. Nevertheless, with complex existence of both generation and power demand points, these approaches and other current detection methods are unable to identify and integrate non-static component of transmission line operation.

Power system network may become unbalanced leading to outages or collapse when there is insufficient capacity on the transmission line to supply power to connected loads from the generation site (Concordia, Fink, & Poullikkas, 1995). Outage and network collapse management processes have become too costly and difficult to carry out routine maintenance. Thus, system operators may decide to shed some power from heavily loaded lines (Saffarian & Sanaye-Pasand, 2010; Taylor, 1992). Hence, Ford, Bevrani, and Ledwich (2009) recommended the elimination of pre-selected customer loads from the power system to preserve integrity of the power system and reduce total customer outages when an irregular condition occurs. However, the pre-selection process remain unsustainable since any criteria applied in the selection will likely eliminate some customers from accessing power. Sudden increase of power demand in a network have been observed to cause overload to transmission line that may not necessarily be already highly loaded. In order to ease the overload of these transmission lines, network reconfiguration was proposed as a means of altering the transmission line power flow path. That is, redispatch of the power flow to load from another transmission line with adequate capacity and tendency under normal operating conditions to alter the performance and power losses on the network (Wu, 2015). The reconfiguration of the network is also used to conserve additional load capacity for useful power flow and maintenance of load balancing (Kashem et al., 1998). Nonetheless, PMU application provides a much clearer view of all the complex parameters of the transmission system, such as technical losses, corona losses, line parameters and transmission capacity (Kim, & Yoon, 2016; Exposito, 2004). To ensure high accuracy of the reciprocal alignment of measurements from both ends of the transmission line, the PMU approach utilizes global positioning system (GPS) signals. In order to define power of the transmission, PMUs are mounted at both ends to calculate different time instants, voltage phasors and current phasors of a transmission line (Phadke & Kasztenny, 2008). Furthermore, state estimation of power system has equally been used to estimate different errors states of the line power flow operations (Patel, 2016).

To overcome non-linear constraints, the Benders decomposition algorithm was developed to define the usable transfer capacity on transmission lines. The algorithm decomposes line operating capacity state into master and slave levels that communicate before convergence (Geoffrion, 1972). The master problem reflects operating condition of the steady state, while the sub-problems represent the contingencies. Each sub-problem is independently solved and a linear constraint is developed and applied to the master problem using Lagrange sub-problem multipliers (Geoffrion, 1972; Dommel & Tinney, 1968). However, the Benders decomposition algorithm is not particularly effective as transmission line switching in the identification of line overload contingency. The transmission line switching is one of the ways in which line capability may be identified as well as serves as a quick measure for the allocation of power flow for relieve of line overload (Li et al., 2011). The mechanism of line switching is to take lines in and out of the power network for purposes, such as optimizing the economic efficiency of dispatch generation and minimising of contingency conditions (Shao & Vittal, 2005; Bacher & Glavitsch, 1988; Fisher, O'Neill, & Ferris, 2008). The method for line switching has also been to carry out maintenance on damaged system modules, eliminate outages due to line overloads, and mitigate losses. For further predictions of insecurity that could occur on the transmission lines, line switching has often been applied (Hedman, Oren, & O'Neill, 2011). As loads varies, so do network security losses and risks. Essentially, line switching affects the configuration of the network, thus has a net impact on the transfer of power through other transmission lines within the same network (Ravindra, Reddy, & Sivanagaraju, 2015). Any of the flows that could cause overload of some lines and network outage maybe diverted through defined lines with low losses within the transmission network.

This paper focuses on recognising transmission line capacity in the operations of network power flow by dispatching the overflow capacity of each line at being overloaded without leading to network collapse or islanding. In addition, two operational levels of the transmission line capacity are considered:

(a) Installed capacity: Which is the expected full load sustained output of a transmission line. The transmission line installed capacity is also known as maximum rated capacity in Mega Watts (MW) for which transmission lines operate under ideal circumstances.

(b) Transmission lines active capacity: Here, a maximum output is measured in MW and completed within a time unit. However, it may be difficult to identify the active power of the transmission line because it is influenced by constantly evolving complex factors at generation and load ends. Hence, to define line power flow, transmission line switching mechanism is used to correct network outage overloads.

As shown, section 1 of this paper gives the introduction. Section 2 is the mathematical modeling of the simulated transmission line, while in section 3, the simulation design criteria is analysed. Section 4 gives the result and discussion. Section 5 presents the conclusion of the paper.

Mathematical Modeling of the Simulated Transmission Line

Mathematical model of the power flow equations for the simulated transmission line switching is presented in this section. Figure 1 shows the simulated IEEE 13-bus test case used to test and analyse the results obtained from the transmission line switching.

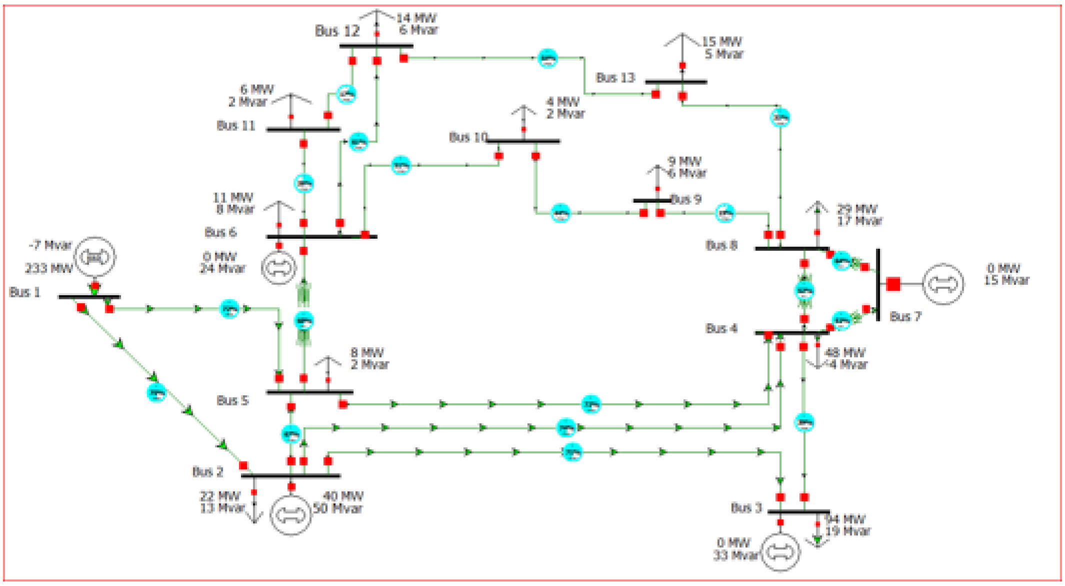

Figure 1. An IEEE 13-Bus network showing power flow

Kirchhoff's Current Law (KCL) requires that each of the current into a junction be equal to the sum of the currents flowing out of the bus and into the lines connecting the bus to other buses (Saadat, 2002). Recall Ohm's Law states that $I = \frac{V}{R} = VY$, the current injected into bus 1 may be written as:

$$I_1 = (V_1 - V_2)Y_{12} + (V_1 - V_5)\,Y_{15} \tag{1}$$

Rearranging equation 1, we have:

$$I_1 = V_1(Y_{12} + Y_{15}) + V_2(-Y_{12}) + V_5(-Y_{15}) \tag{2}$$

Similarly, the current injections at buses 2, 3, up to bus 13 in Figure 1 maybe developed as:

$$I_2 = V_1(-Y_{12}) + V_2(Y_{12} + Y_{23} + Y_{24} + Y_{25}) + V_3(-Y_{23}) + V_4(-Y_{24}) + V_5(-Y_{25}) \tag{3}$$

$$I_3 = 0 + V_2(-Y_{23}) + V_3(Y_{23} + Y_{34}) + V_4(-Y_{34}) \tag{4}$$

$$I_4 = 0 + V_2(-Y_{24}) + V_3(-Y_{34}) + V_4(Y_{24} + Y_{34} + Y_{45}) + V_5(-Y_{45}) \tag{5}$$

Mathematical Formulation of a Transmission Line

Consider the Π (pi) representation of a transmission line shown in Figure 2. Using Kirchhoff's Current Law (KCL) at bus i, given as:

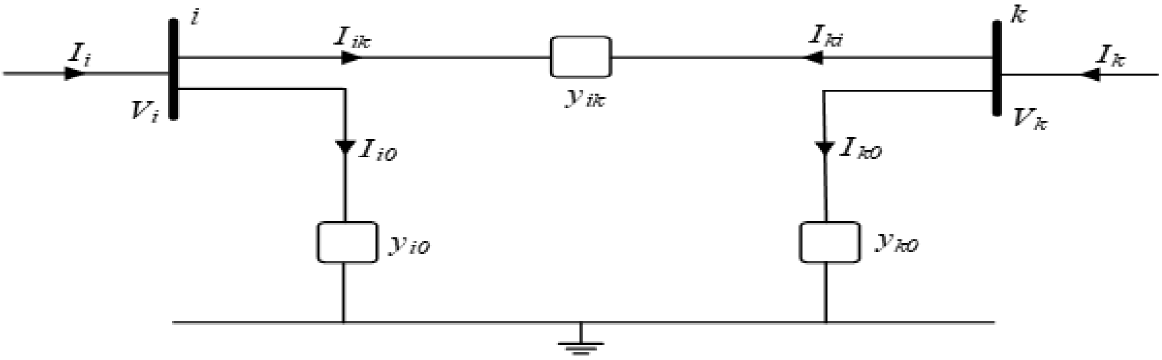

Figure 2. Representation of a transmission line (Saadat, 2002)

$$I_i = I_{ik} + I_{io} \tag{6}$$

where, $I = \frac{V}{R} = VY$ (Ohm's law)

Therefore at bus I (Figure 1)

$$I_i = (V_i - V_k - Y_{ik}) + V_i y_{io} \quad (7)$$

$$S_{ik} = V_i I^*_{ik} \quad (8)$$

Substituting for I_i from (6)

$$S_{ik} = V_i[(V_i - V_k)y_{ik} + V_i y_{io}]^* \quad (9)$$

Similarly applying KCL at bus k we have:

$$I_k = I_{ki} + I_{ko} \quad (10)$$

$$I_k = (V_k - V_i)\, y_{ki} + V_k y_{ko} \quad (11)$$

$$S_{ki} = V_k I^*_{ki} \quad (12)$$

$$S_{ki} = V_k[(V_k - V_i)y_{ki} + V_k y_{ko}]^* \quad (13)$$

where,

I_i & I_k are the currents injected into buses i and k respectively, V_i & V_k are the voltages at buses i and k respectively.

I_{ik} & I_{ki} are the current flows from bus i to k and k to i respectively

I_{io} & I_{ko} are the shunt currents, y_{io} & y_{ko} are the shunt admittances at buses i and k respectively

y_{ik} & y_{ki} are the line admittances from bus i to k and k to i respectively

S_{ik} & S_{ki} are the complex powers from bus i to k and k to i respectively

P_{ik} & Q_{ki} also P_{ki} & Q_{ik} both real and reactive power flows.

Equations (9) and (13) are the line flows between the buses.

However, real power flow between two buses may be obtained from:

$$P_R = \frac{V_S \times V_R}{X} \times \sin\delta \quad (14)$$

where,

P = Real power in MW

V_S = Sending-end voltage

V_R = Receiving-end voltage

X = Line impedance between buses

ä = Angle delta between bus voltages

Angle theta (è) represents the angle difference between current and voltage used in determining power factor indicating the portion of total current and voltage that is producing real power. Angle delta (ä) represents the phase angle difference between the sending and receiving voltages. In this paper, negative MW indicate flow into the sending bus while positive MW indicate flow out of the sending bus (Miller & Malinowski, 1994).

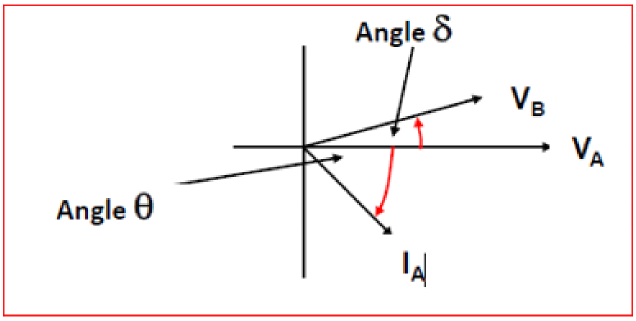

Figure 3. Transfer power between two points of a system phasor diagram (Miller & Malinowski, 1994)

Figure 3 shows that there must be an angle ä between voltages at either end of the line in order to pass actual power through a transmission line. The greater difference in phase angle results in more actual power transferred. High impedance results in decrease in transfer of real power, thus increasing the difference in phase angle increases the transfer of real power. If impedances of parallel lines are equal, power flow is similarly distributed, and if impedances of parallel lines are different, real power flow is inversely proportional to line impedance (Miller & Malinowski, 1994). Hence, neither increasing nor decreasing voltage magnitudes have a major impact on the flow of real power.

The reactive power (Q_R) flow on a transmission line is a function of the load requirements inductive reactance and is obtained by:

$$Q_R = \frac{V_S \times \Delta V}{X} \times \cos\delta \tag{15}$$

where,
Q = Reactive power in MVAR
V_S = Sending-end voltage
ÄV = Difference between bus voltages V_S and V_R
X = Line Impedance between buses
è = Phase angle between V_S and V_R

The VAR only flows downhill from a higher per unit value to a lower per unit voltage value if there is a difference in the bus voltage potential. The negative VAR value indicates the reference bus flow while the positive VAR value indicates the reference bus flow. The reactive power flow towards the receiving end is increased by increasing the voltage magnitude at the sending end and the reactive power flow towards the receiving end is decreased by increasing the voltage magnitude at the receiving end (Miller & Malinowski, 1994). The reactive power flow towards the receiving end and is decreased by increasing the path impedance between the two buses. To acquire the capacity available for each line in MVA:
Available Capacity = Installed Capacity - Operating Capacity

Simulation Design Criteria

Design of Transmission Line when All Lines are not Switched

A modified IEEE 13-Bus network depicted in a PowerWorld drawing as shown in Figure 4. The branches connecting the buses reflect the steady state of the transmission lines, where no line is overloaded. The network consists of 19 transmission lines labelled with respect to the interconnecting buses of the line as shown in Figure 4. These transmission lines signify the available link between two buses including 5 generator buses in the network. The network is considered to be at steady state flat start operation. The initial simulation is with no line switched out of the network and no overload on any line was observed.

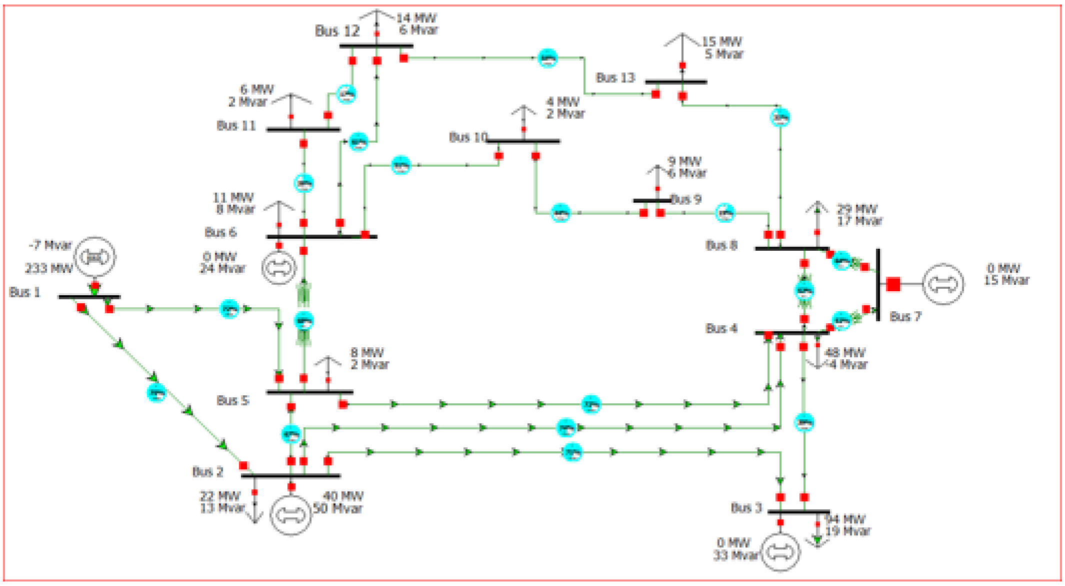

Figure 4. The Modified IEEE 13-Bus network when no line is switched out of the network

Design of Transmission Line when a Line is Switched Out

Figure 5 shows the simulation when line L_{2-5} is switched out of the network and depicts no occurrence of collapse or islanding. The switching of line L_{2-5} shows no network overload, however it may be observed that the available capacity on L_{2-3} is close to being overloaded.

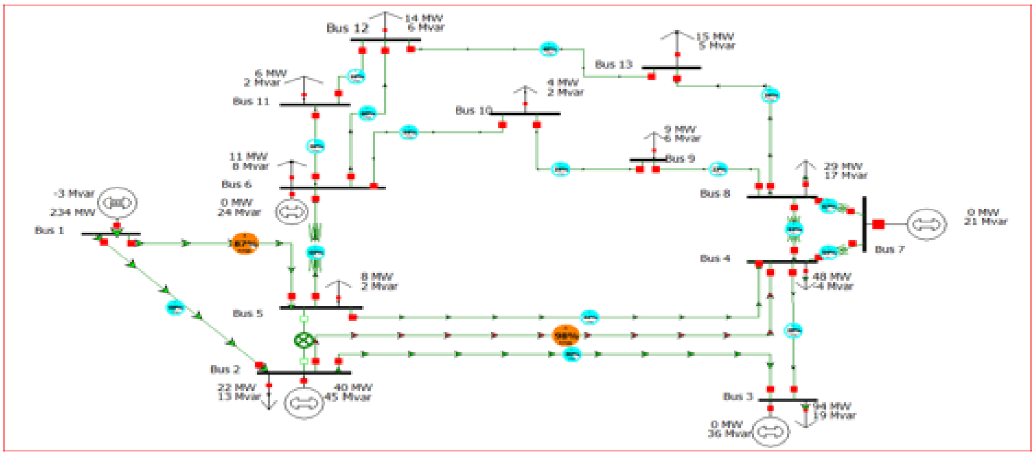

Figure 5. Line 2-5 (L_{2-5}) is switched out of the network

Through the PowerWorld Simulator, switching of transmission lines in/out the network is executed. This enabled evaluation of real and reactive power flows through the transmission line network. Some of the flows that could cause overload of certain lines, outage and possible collapse are dispatched to established lines within the transmission network.

Results and Discussion

Table 1. Line data at steady state when no line is switched out of the network

Number of Lines	Line Name	Line Status	Real Power (MW)	Reactive Power (Mvar)	Operating Capacity (MVA)	Installed Capacity (MVA)	Available Capacity (MVA)
1	L_{1-2}	Closed	157.5	-15.4	158.3	200	41.7
2	L_{1-5}	Closed	75.4	8.2	75.9	100	24.1
3	L_{2-3}	Closed	73.8	3.8	73.9	100	26.1
4	L_{2-4}	Closed	-54.4	-1.0	54.4	73	18.6
5	L_{2-5}	Closed	-40.7	-3.4	40.8	60	19.2
6	L_{3-4}	Closed	23.2	-10.8	25.5	65	39.5
7	L_{4-5}	Closed	61.7	-4.7	61.8	85	23.2
8	L_{4-7}	Closed	28.5	4.5	28.8	55	26.2
9	L_{4-8}	Closed	-16.2	-4.0	16.6	32	15.4
10	L_{5-6}	Closed	-44.0	-0.7	44.0	65	21.0
11	L_{6-10}	Closed	7.1	5.9	9.2	18	8.8
12	L_{6-11}	Closed	-7.8	-2.6	8.2	32	23.8
13	L_{6-12}	Closed	-17.6	-8.0	19.3	32	12.7
14	L_{7-8}	Closed	-28.5	-16.8	33.1	52	18.9
15	L_{8-9}	Closed	-5.5	-2.0	5.9	32	26.1
16	L_{8-13}	Closed	-9.4	-1.9	9.6	32	22.4
17	L_{9-10}	Closed	3.5	3.9	5.2	12	6.8
18	L_{11-12}	Closed	-1.7	-1.0	2.0	12	10.0
19	L_{12-13}	Closed	5.5	3.2	6.4	12	5.6

Figure 6 shows the graphical display of the available capacity when no line is switched out of the network. The blue graph indicates that the network has available capacity with no line overload.

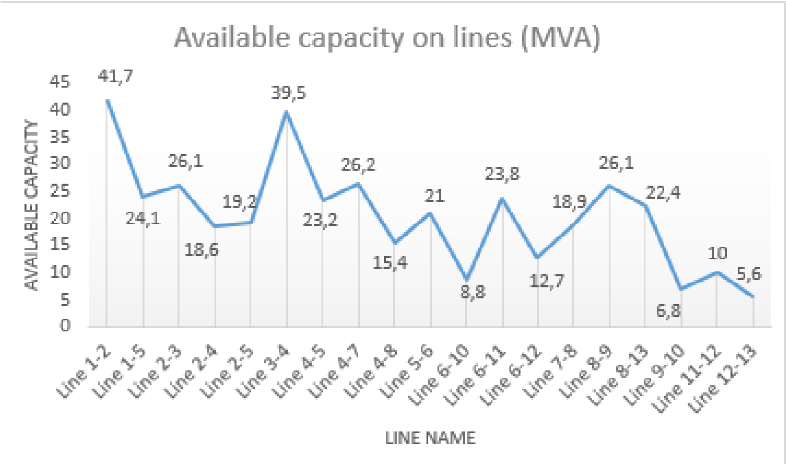

Figure 6. Available Capacity when no line is switched out of the network

For the simulation of L_{1-2} switched out of network resulted in overload of lines L_{1-5} and L_{4-5} respectively. However, lines L_{3-4} and L_{7-8} show closeness to being overloaded. Table 2 and Figure 7 give the results and the graphical display of the available capacity when L_{1-2} is switched out of the network.

Table 2. Line data when L_{1-2} is switched out of the network

Line	Line Name	Line Status	Any Overload	Number of Overload	Percentage Overload (%)	Real Power (MW)	Reactive Power (Mvar)	Operating Capacity (MVA)	Installed Capacity (MVA)	Available Capacity (MVA)
1	L_{1-2}	Open	Yes	2	-	-	-	-	-	-
2	L_{1-5}	Closed	-	-	2.57	263.6	69.1	272.5	100	-
3	L_{2-3}	Closed	-	-	-	48.0	1.8	48.1	100	51.9
4	L_{2-4}	Closed	-	-	-	-1.9	-11.8	12.0	73	61.0
5	L_{2-5}	Closed	-	-	-	32.8	-24.0	40.6	60	19.4
6	L_{3-4}	Closed	-	-	-	49.4	-15.8	51.8	65	13.2
7	L_{4-5}	Closed	-	-	1.88	140.7	-50.0	149.3	85	-
8	L_{4-7}	Closed	-	-	-	27.2	-26.2	37.8	55	17.2
9	L_{4-8}	Closed	-	-	-	-14.8	3.8	15.3	32	16.7
10	L_{5-6}	Closed	-	-	-	-46.8	10.5	47.9	65	17.1
11	L_{6-10}	Closed	-	-	-	8.9	-1.0	9.0	18	9.0
12	L_{6-11}	Closed	-	-	-	-7.8	-1.7	8.0	32	24.0
13	L_{6-12}	Closed	-	-	-	-18.4	-4.5	19.0	32	13.0
14	L_{7-8}	Closed	-	-	-	27.2	-36.0	45.1	52	6.9
15	L_{8-9}	Closed	-	-	-	-3.7	-8.8	9.6	32	22.4
16	L_{8-13}	Closed	-	-	-	-8.6	-6.3	10.7	32	21.3
17	L_{9-10}	Closed	-	-	-	5.3	-2.9	6.1	12	5.9
18	L_{11-12}	Closed	-	-	-	-1.7	-0.1	1.7	12	10.3
19	L_{12-13}	Closed	-	-	-	6.4	-1.2	6.5	12	5.5

The red line graph indicates that although some lines have available capacity but there is no available capacity in the network because there are lines that caused overload therefore the network is considered to be out of operation.

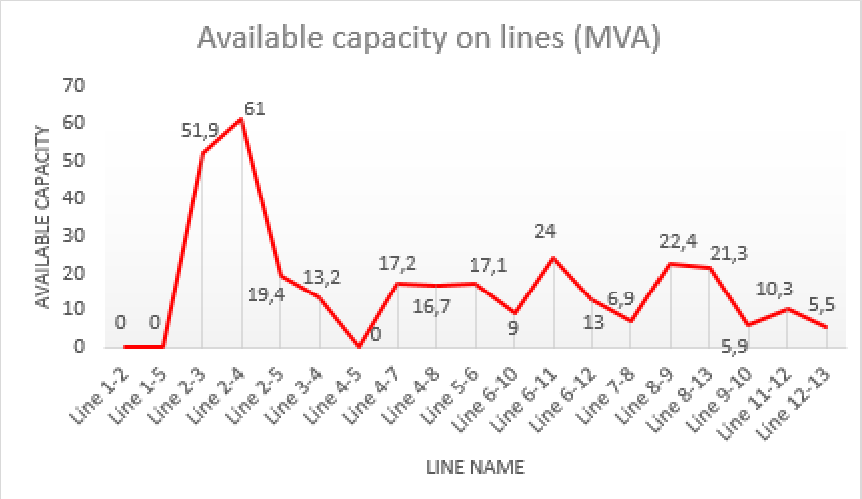

Figure 7. Available Capacity when L_{1-2} is switched out of the network

Figure 8 gives the graphical display of the percentage overload when L_{1-2} is switched out of the network.

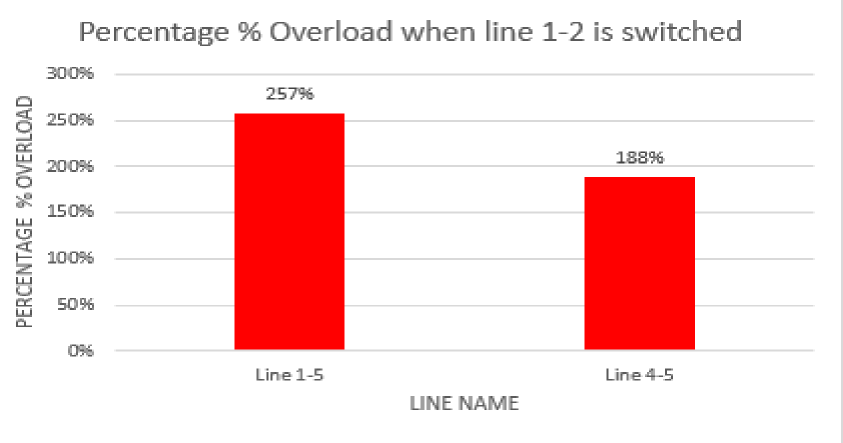

Figure 8. Percentage Overload when L_{1-2} is switched out of the network

When L_{2-5} was switch out, Table 3 gives the data obtained.

Table 3. Line data when L_{1-5} is switched out of the network

Line	**Line Name**	**Line Status**	**Any Overload**	**Number of Overload**	**Percentage Overload (%)**	**Real Power (MW)**	**Reactive Power (Mvar)**	**Operating Capacity (MVA)**	**Installed Capacity (MVA)**	**Available Capacity (MVA)**
1	L_{1-2}	Closed	-	-	1.14	240.7	-5.1	240.7	200	-
2	L_{1-5}	Open	Yes	3	-	-	-	-	-	-
3	L_{2-3}	Closed	-	-	-	87.5	1.1	87.6	100	12.4
4	L_{2-4}	Closed	-	-	1.11	-79.6	8.4	80.1	73	-
5	L_{2-5}	Closed	-	-	1.27	-74.7	5.6	74.9	60	-
6	L_{3-4}	Closed	-	-	-	10.2	-10.8	14.9	65	50.1
7	L_{4-5}	Closed	-	-	-	25.9	-9.1	27.4	85	57.6
8	L_{4-7}	Closed	-	-	-	30.4	-5.4	30.9	55	24.1
9	L_{4-8}	Closed	-	-	-	-17.0	-1.3	17.1	32	14.9
10	L_{5-6}	Closed	-	-	-	-41.2	2.5	41.3	65	23.7
11	L_{6-10}	Closed	-	-	-	5.4	3.9	6.7	18	11.3
12	L_{6-11}	Closed	-	-	-	-7.5	-2.4	7.9	32	24.1
13	L_{6-12}	Closed	-	-	-	-16.8	-7.0	18.2	32	13.8
14	L_{7-8}	Closed	-	-	-	-30.4	-22.5	37.8	52	14.2
15	L_{8-9}	Closed	-	-	-	-7.1	-3.8	8.1	32	23.9
16	L_{8-13}	Closed	-	-	-	-10.6	-3.1	11.0	32	21.0
17	L_{9-10}	Closed	-	-	-	1.9	2.0	2.7	12	9.3
18	L_{11-12}	Closed	-	-	-	-1.4	-0.8	1.6	12	10.4
19	L_{12-13}	Closed	-	-	-	4.4	2.0	4.8	12	7.2

Figure 9 gives the graphical display of the available capacity when L_{1-5} is switched out of the network. The red graph indicates that although some lines has the available capacity but there is no available capacity in the network because there are lines that caused overloading therefore the network is considered to be out of operation.

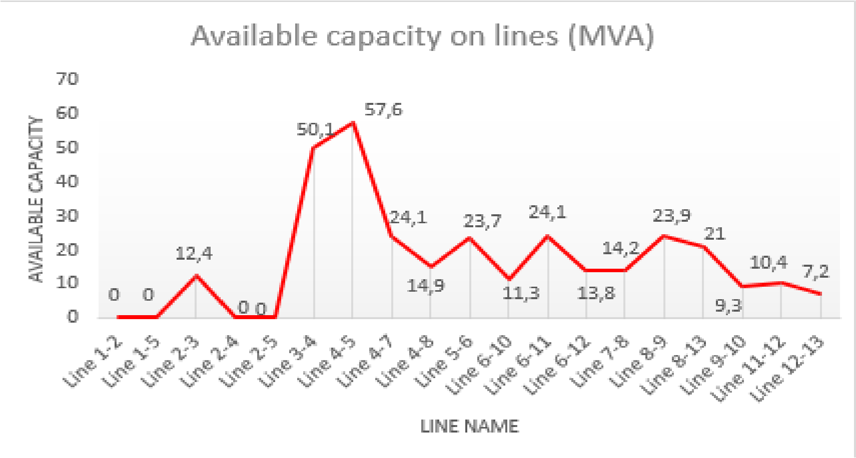

Figure 9. Available Capacity when L_{1-5} is switched out of the network

Figure 10 gives the graphical display of the percentage overload when L_{1-5} is switched out of the network.

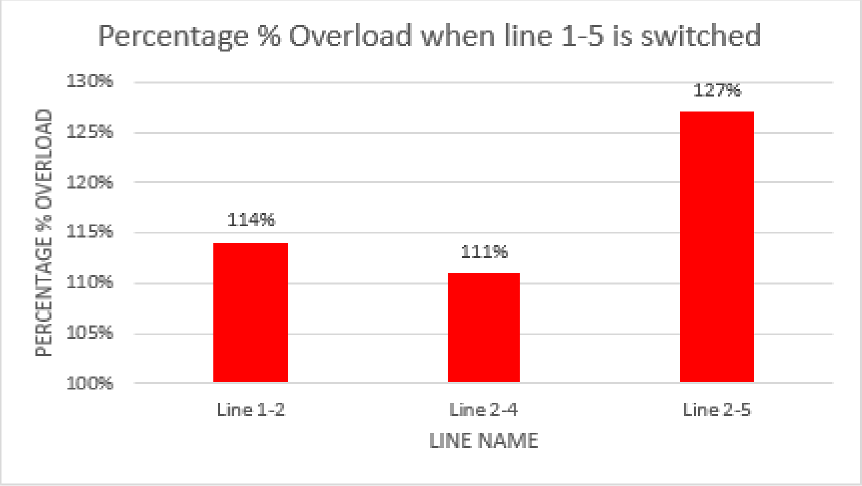

Figure 10. Percentage Overload when L_{1-5} is switched out of the network

It may be observed that when L_{2-3} was switched out it resulted in overload of lines L_{2-4}, L_{2-5}, L_{3-4} and L_{4-5} respectively. However, L_{1-5} shows closeness to being overloaded as compared to other lines.

Table 4. The line data when L_{2-3} is switched out of the network

Line	**Line Name**	**Line Status**	**Any Overload**	**Number of Overload**	**Percentage Overload (%)**	**Real Power (MW)**	**Reactive Power (Mvar)**	**Operating Capacity (MVA)**	**Installed Capacity (MVA)**	**Available Capacity (MVA)**
1	L_{1-2}	Closed	-	-	-	149.2	-12.2	149.7	200	50.3
2	L_{1-5}	Closed	-	-	-	95.0	15.0	96.2	100	3.8
3	L_{2-3}	Open	Yes	4	-	-	-	-	-	-
4	L_{2-4}	Closed	-	-	1.24	-89.4	3.5	89.5	73	-
5	L_{2-5}	Closed	-	-	1.12	-66.8	-1.6	66.9	60	-
6	L_{3-4}	Closed	-	-	1.58	101.3	-4.4	101.4	65	-
7	L_{4-5}	Closed	-	-	1.23	103.9	-4.5	104.0	85	-

8	L_{4-7}	Closed	-	-	-	27.4	-6.3	28.1	55	26.9
9	L_{4-8}	Closed	-	-	-	-15.4	-1.2	15.4	32	16.6
10	L_{5-6}	Closed	-	-	-	-45.9	2.0	45.9	65	19.1
11	L_{6-10}	Closed	-	-	-	8.2	4.2	9.3	18	8.7
12	L_{6-11}	Closed	-	-	-	-7.9	-2.4	8.3	32	23.7
13	L_{6-12}	Closed	-	-	-	-18.2	-7.1	19.5	32	12.5
14	L_{7-8}	Closed	-	-	-	-27.4	-22.3	35.3	52	16.7
15	L_{8-9}	Closed	-	-	-	-4.4	-3.6	5.7	32	26.3
16	L_{8-13}	Closed	-	-	-	-8.8	-3.0	9.3	32	22.7
17	L_{9-10}	Closed	-	-	-	4.6	2.3	5.2	12	6.8
18	L_{11-12}	Closed	-	-	-	-1.8	-0.8	2.0	12	10.0
19	L_{12-13}	Closed	-	-	-	6.2	2.1	6.5	12	5.5

Figure 11 gives the graphical display of the available capacity when L_{2-3} is switched out of the network. The red line graph indicates that although some lines have available capacity but there is no available capacity in the network because there are lines that caused overload the network is again considered as being out of operation.

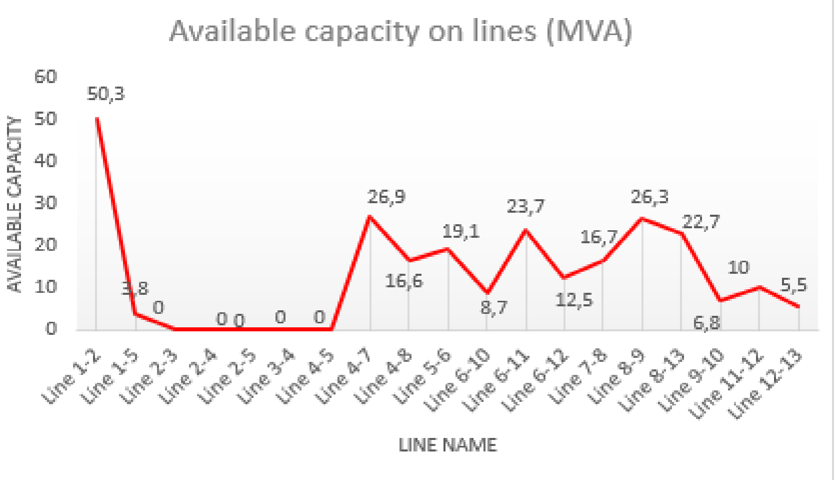

Figure 11. Available Capacity when L_{2-3} is switched out of the network

Figure 12 gives graphical display of the percentage overload when L_{2-3} is switched out of the network.

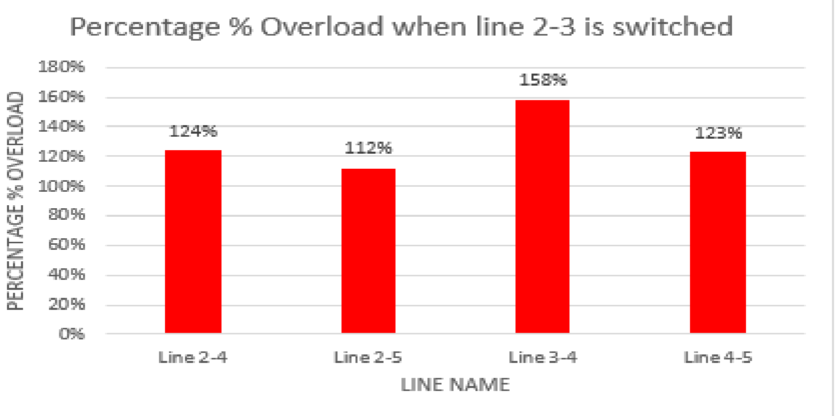

Figure 12. Percentage Overload when L_{2-3} is switched out of the network

Other lines were also switched out for the network with a summarized result shown in Table 5.

Table 5. Analysis of the network when the 19 lines are each switched out of service

Line	Switched lines	Any Overload	Number of Overload	Percentage Overload (%)	Network available capacity (MVA)
1	L_{1-2}	Yes	2	$L_{1-5} = 2.57$	No available capacity
2	L_{1-5}	Yes	3	$L_{1-2} = 1.14$ $L_{2-4} = 1.11$ $L_{2-5} = 1.27$	No available capacity
3	L_{2-3}	Yes	4	$L_{2-4} = 1.24$ $L_{2-5} = 1.12$ $L_{3-4} = 1.58$ $L_{4-5} = 1.23$	No available capacity
4	L_{2-4}	Yes	2	$L_{2-5} = 1.07$ $L_{4-5} = 1.16$	No available capacity
5	L_{2-5}	No	-	-	364.8
6	L_{3-4}	No	-	-	355.8
7	L_{4-5}	Yes	2	$L_{2-4} = 1.18$ $L_{9-10} = 1.07$	No available capacity
8	L_{4-7}	Yes	1	$L_{9-10} = 1.02$	No available capacity
9	L_{4-8}	No	-	-	347.1
10	L_{5-6}	Yes	8	$L_{4-5} = 1.17$ $L_{4-7} = 1.06$ $L_{4-8} = 1.02$ $L_{6-10} = 1.22$ $L_{7-8} = 1.21$ $L_{8-9} = 1.09$ $L_{9-10} = 2.11$ $L_{12-13} = 1.10$	No available capacity
11	L_{6-10}	No	-	-	361.5
12	L_{6-11}	No	-	-	352.6
13	L_{6-12}	Yes	1	$L_{11-12} = 1.23$	No available capacity
14	L_{7-8}	Yes	4	$L_{4-8} = 1.02$ $L_{6-10} = 1.16$ $L_{9-10} = 1.38$ $L_{12-13} = 1.19$	No available capacity
15	L_{8-9}	No	-	-	338.7
16	L_{8-13}	Yes	1	$L_{12-13} = 1.43$	No available capacity
17	L_{9-10}	No	-	-	377.0
18	L_{11-12}	No	-	-	394.5
19	L_{12-13}	No	-	-	378.2

Table 6. Analysis the lines when switched with no overload in the network

Number of lines	Switched lines that result in no overloading in the network	Available Capacity on the network (MVA)
1	L_{2-5}	364.8
2	L_{3-4}	355.8
3	L_{4-8}	347.1
4	L_{6-10}	361.5
5	L_{6-11}	352.6
6	L_{8-9}	338.7
7	L_{9-10}	377.0
8	L_{11-12}	394.5
9	L_{12-13}	378.2

A difference in the installed capacity and the operating capacity in MVA is used to obtain the available capacity in each transmission line of the network.

Conclusion

The installed capacity of the transmission lines of network are determine at planning stage of the power system. However when the lines are in service, the installed capacity is not completely utilised by the power flow due to the interconnections that occur between low and high capacity lines present in the same network. However to achieve full power flow potential of the network, the operation of certain overload and outage corrections lines is used. To obtain the available power of a network, the transmission line switching technique has been introduced. It is observed that because an overload on any line means an unstable network, no line in the network should be overloaded. However, there might still be some available capacity for the lines in the network that do not encounter overload. This strategy requires transmission system operators to withdraw the line from service in order to enhance the functioning of the network during outages and maintenance.

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