Contingency Analysis of Ethiopia's 230 kV Transmission Network

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Abstract - Transmission line congestion is any one of the failures that leads the overall transmission network to be either in overloaded or underloaded condition. Loading effects of the entire network may lead the system to cascaded outage or total blackout. The study concentrated on the contingency analysis of Ethiopia's 230KV transmission network a case of Sebeta to Kaliti transmission line. The outage of this line causes overloading on Gefersa to Kaliti transmission line and makes the system not to be secure and reliable; further cascaded outage will lead the system to the total blackout. The analysis has been conducted by considering four scenarios such as a normal state, single line outage, cascaded line outage and inserting Distributed Static Series Compensator (DSSC) into the overloaded line. As a result, the system became reliable and secure by inserting the device in the most sensitive line of the network.

Keywords - Contingency analysis, D-FACTS devices, transmission network.

1. Introduction

Contingency is a failure of any power system equipment from the network due to some emergency situations [1]. Transmission line congestion is any one of the failures that leads the overall transmission network to be either in overloaded or underloaded state. Contingency analysis enables the system to be operated effectively. The major problems that occur in power system can cause serious damage within a short time if the operator could not take an immediate corrective action.

Ethiopia electric power transmission network is more complicated due to the centralized grid interconnection system. Therefore, a loss of one transmission line from the network will gradually disturb the rest of the system. The network needs latest autonomous control and protective mechanisms on the selected transmission line to make the system secure.

Power flow control is the ability to control the distribution of power flow among transmission lines with respect to transmission line reactance. The power flow control through the transmission lines enable to use the existing power system efficiently. Especially, maintaining reliable and secure electric power is required during the system component congestion, typically transmission line outage. Varying transmission line reactance can be achieved with the help of electronic devices, capable of injecting variable reactance (inductance or capacitance), depending on the situation.

Distributed Flexible AC Transmission System (D-FACTS) devices are a new technological device used to inject the reactance depending upon the condition. The devices are the best solutions to control power flow through transmission lines in terms of size, cost and efficiency, typically Distributed Static Series Compensator (DSSC), by injecting reactance. İt balances the power flow distribution through the overall network during the line outage; assuring power system reliability and security.

2. D-FACTS Component and Operatıon

D-FACTS devices may facilitate the realization of a comprehensive controllable power system. Large-scale power flow control may finally be achievable [2, 3].

The DSSC system is made up of a large number of modules, each module contains a small rated single phase inverter (10~20 kW), a communication link and a single turn transformer (STT) which can be mechanically clamped on to or suspended from the transmission line conductor. STT has a transmission conductor as secondary winding and injects the desired voltage in the cable itself [4]. The inverter is self-powered by induction from the line and injects a voltage that is orthogonal to the current. The module can be suspended from the conductor. The STT remains in bypass mode until the inverter is activated and a DC control of the power supply transformer gets excited with the STT secondary winding current. The DSSC schematic diagram is shown in fig. 1 below.

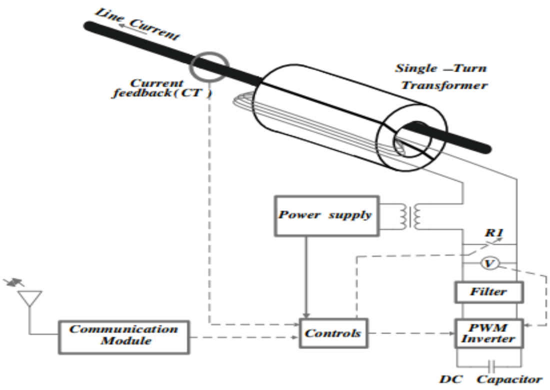


Fig. 1. Schematic diagram of DSSC [5]

Large numbers of DSSCs devices are clamped to conductors of a transmission line to control the line reactance [6]. This feature provides variation in line reactance which results in control of power flow. There is no requirement of phase-ground insulation for DSSC hence has a flexibility of clamping it to any transmission line irrespective of its voltage level [7].

The concept of D-FACTS presents the highest potential to increase power flow and consequently the transfer capacity of a meshed transmission, sub-transmission, and distribution network. In a meshed transmission and distribution network, the power transfer capacity of the system is constricted by the first line that reaches the thermal limit. The inability to effectively power flow control in such a network results in significant under utilization of the overall system.

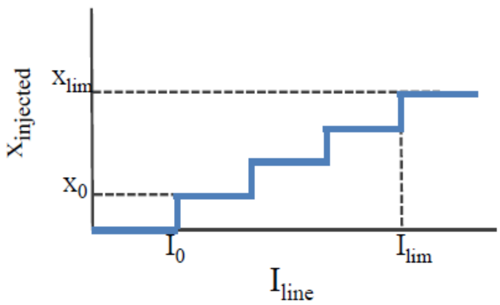


Fig. 2. Operating ranges of D-FACTS [8]

D-FACTS devices offer the ability to improve the transfer capacity and grid utilization by routing power flow from overloaded lines to underutilized parts of the network. Capacitive compensation on underutilized lines would make them more receptive to the inflow of the current, while inductive compensation on overloaded lines would make them less attractive to current flow [9]. In both cases, the whole system is increased by diverting additional power flow from the congested parts of the network to the lines with available capacity using eq. (1) [8, 10] as follows:

$$\text{No. of D} - \text{FACTS} = \frac{(\%\ \text{max.compensation}) * (\text{Tline inductance})}{(\text{Inductance per module})} \quad (1)$$

I_0 = % of rated current (where the percentage is less or equal to 100);

I_{lim} = % of rated current (where the percentage is greater than or equal to 100).

3. Methodology

To achieve the study, the following methods have been used such as data collection and analysis, some reasonable assumptions and case studies have been conducted. The data collected were available in the National Grid Control Center (NGCC) including both numerical system data and single line diagram of Ethiopia's power system network.

The study considered the secondary data that are taken from the Ethiopia Electric Power Corporation (EEPCO) at peak load since 2012 whereas some missing data are filled by data filling software.

In this study, 132KV & 400KV transmission lines have been converted to 230 KV by reducing the thermal limit (A) with the same factor in order to make compatible grid but the MVA limit of the transmission line still remains the same.

A. Transmission Line per unit calculation

$$Z_{pu} = \frac{Z_{actual}}{Z_{base}} \quad (2)$$

Where, $Z_{pu} = R_{pu} + jX_{pu}$

$$Z_{base} = \frac{V_{base}^2}{S_{base}} \quad (3)$$

$$\text{MVA limit} = \sqrt{3} * (V_L * I_{lim}) \quad (4)$$

100 MVA is taken as a base apparent power (S_{base}) for all systems per unit analysis. In addition, base voltages remain the same throughout each line of the network.

Table 1. System input data

Node to Node	R(pu)	X(pu)	B(pu)	MVA limit
Gondar II to B/Dar II	0.000017	0.000061	0.000000306	398
B/Dar II to D/Markos	0.012624	0.086894	0.005267	418
D/Markos to Fincha	0.008054	0.055485	0.000336	418
Fincha to Ghedio	0.008523	0.054260	0.000309	398
Ghedio to GGB I	0.017929	0.101120	0.000616	367
GGB I to GGB II	0.000234	0.000266	0.000014	1217
Gondar II to Alamata	0.060390	0.210050	0.002099	120
B/Dar II to Alamata	0.137508	0.484438	0.042366	355
Alamata to Kaliti	0.084927	0.293071	0.029946	120
Beles to B/Dar II	0.0082	0.12152	0.00120576	1217
Beles to Gefersa	0.001909	0.13007	0.00081162	1217
Wolkite to GGB I	0.000413	0.002809	0.00017644	418
Ghedio to Gefersa	0.004219	0.026859	0.00015307	398

B. Load Input Data Analysis

The study considered substations and distribution centers except the above selected substation as a load, and their data under main load bus bar are summed up to reduce the system complexity. Some of the load is shifted to the appropriate load bus bar and considered as being supplied from it.

Single Line Diagram and Assumptions

As it has been explained above, to come up with an only 230KV grid many assumptions have been done to reduce the whole complex single line diagram into the simple and interesting one. This enforcement was brought due to the limitation of bus bars allowed by software that has been used (only about 13 bus bars are allowed). Accordingly; the 230KV transmission grid is selected even if all 230KVs are not used, since there are about twenty 230KV bus bars. Consequently; shifting of serial bus bars to other bus bar mechanism has been used for the purpose of reducing to 13 bus bars (limited for free access). Except 230KV transmission grid, the whole system has been considered as a load to be supplied from 230KV network. Single line diagram of 230KV transmission network to be studied is shown in fig. 3 below.

DSSC Specification

The DSSC devices to be clamped on the lines should meet the capability of injecting sufficient reactance in accordance with the line fault current. The devices should be specified properly by considering line current flows through a targeted transmission line in both normal and emergency states.

Before the implementation of DSSC, it is obligatory to know the targeted transmission line rated and present flow of currents as well as its impedance. DSSC should be compatible with rated currents of transmission line. Its activation (triggering) current should neither below the expected nor above the rated current. If the triggering current is below the expected, it will start injecting impedance at normal state, but it was no need to do so. Whereas, the transmission line treatment using DSSC devices will be under question when it is above the rated current. Therefore, protective devices will take the action before them depending on the sequence of event execution.

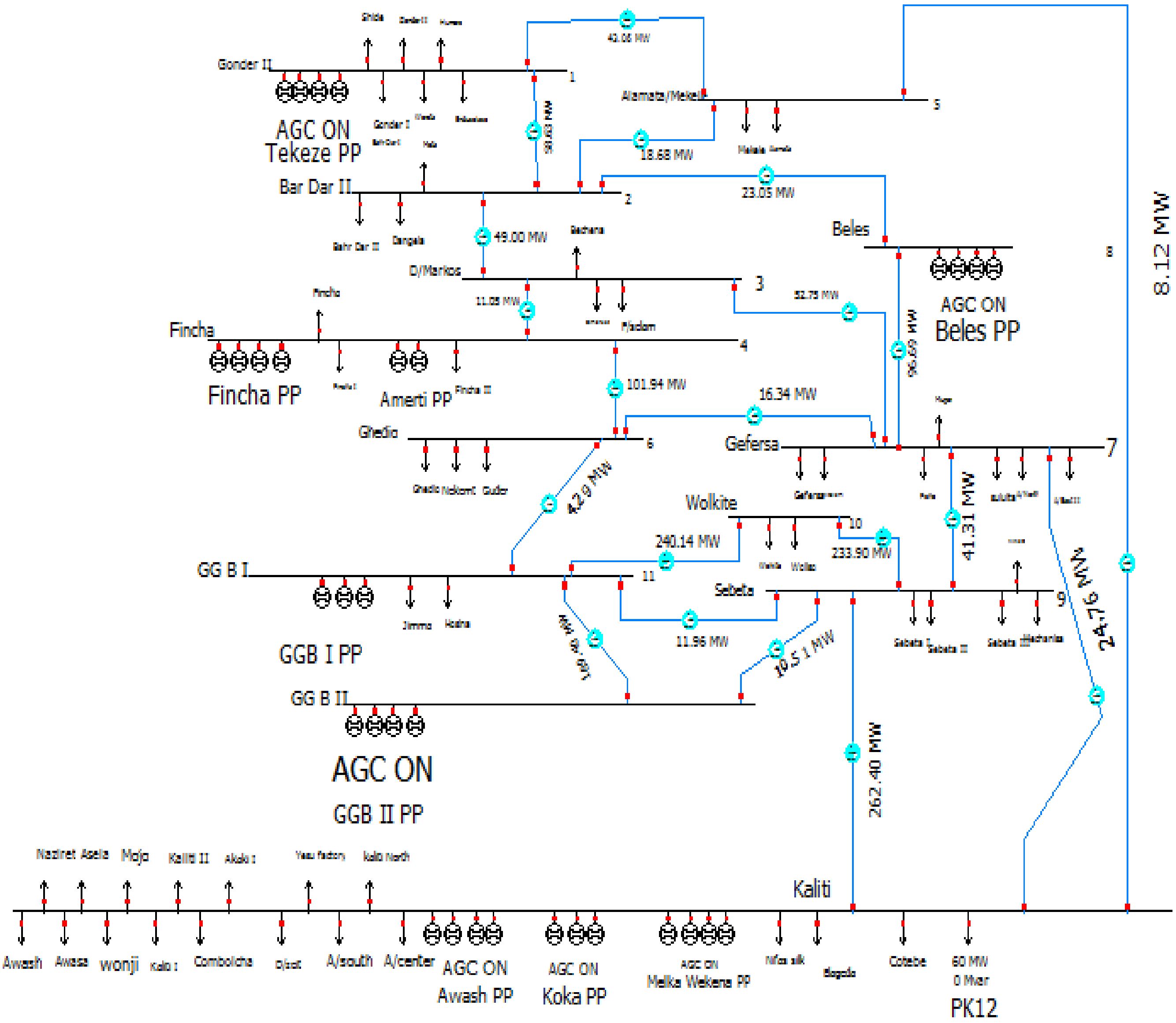


Fig. 3. Single line diagram of 230KV grid

Case Studies

The case has been conducted on the line outage from Sebeta to Kaliti as being informed by NGCC. The study considered four cases for further investigation of the line outage effect analysis.

Case One: - Normal State

As per the collected data from Dispatch Center most of the time outage of a single transmission line on the network does not have more effects over others.

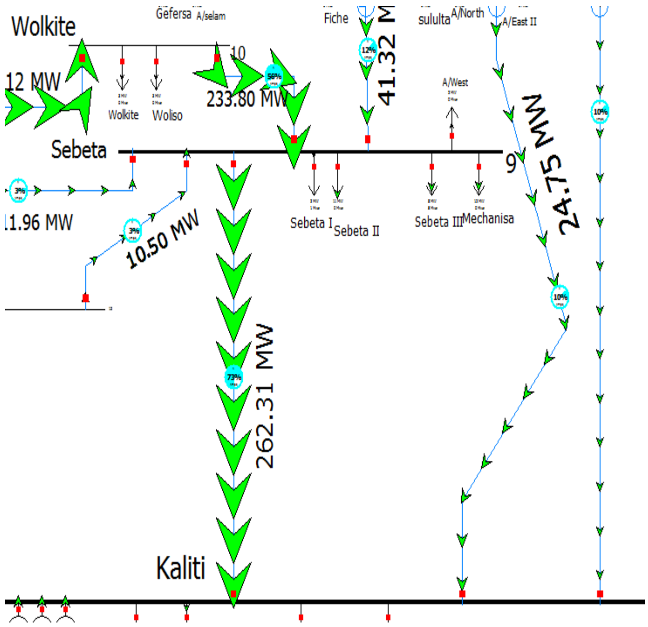


Fig. 4. Line normal state

The outage of Sebeta to Kaliti transmission line causes for a loading effect over others that lead the network to a partial blackout. The line is even overloaded (about 73% loading) under normal condition as shown in the fig. 4 above.

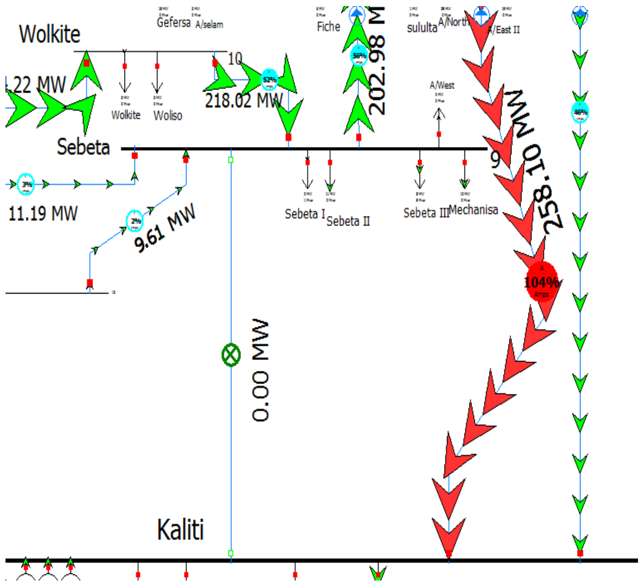


Fig. 5. Simulation results during line outage

Case Two:- When Sebeta to Kaliti Line is out of the system

Sebeta to Kaliti line outage causes highly overloading of Gefersa to Kaliti line which have a line loading of 104% as shown in the fig. 5 above. It indicates that the line will go to emergency and alert states because of its loading beyond their rated capacity.

Case Three:- The cascaded outage of Sebeta to Kaliti and Gefersa to Kaliti

Since, the outage of Sebeta to Kaliti causes overload on Gefersa to Kaliti transmission line.

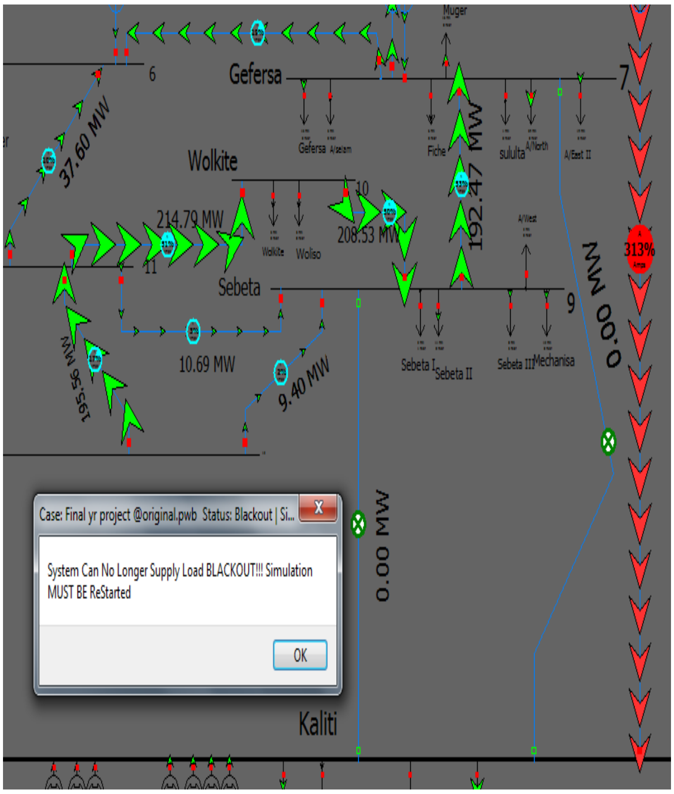


Fig. 6. The total black out due to cascaded outage

Due to this reason, the protective devices (relay and circuit breaker) are forced to trip the line from the system then a cascaded outage is happening. Finally, this cascaded outage will cause a total blackout as shown in fig. 6 above.

Case Four: - Outage of Sebeta to Kaliti line and the effect of using D – FACT devices

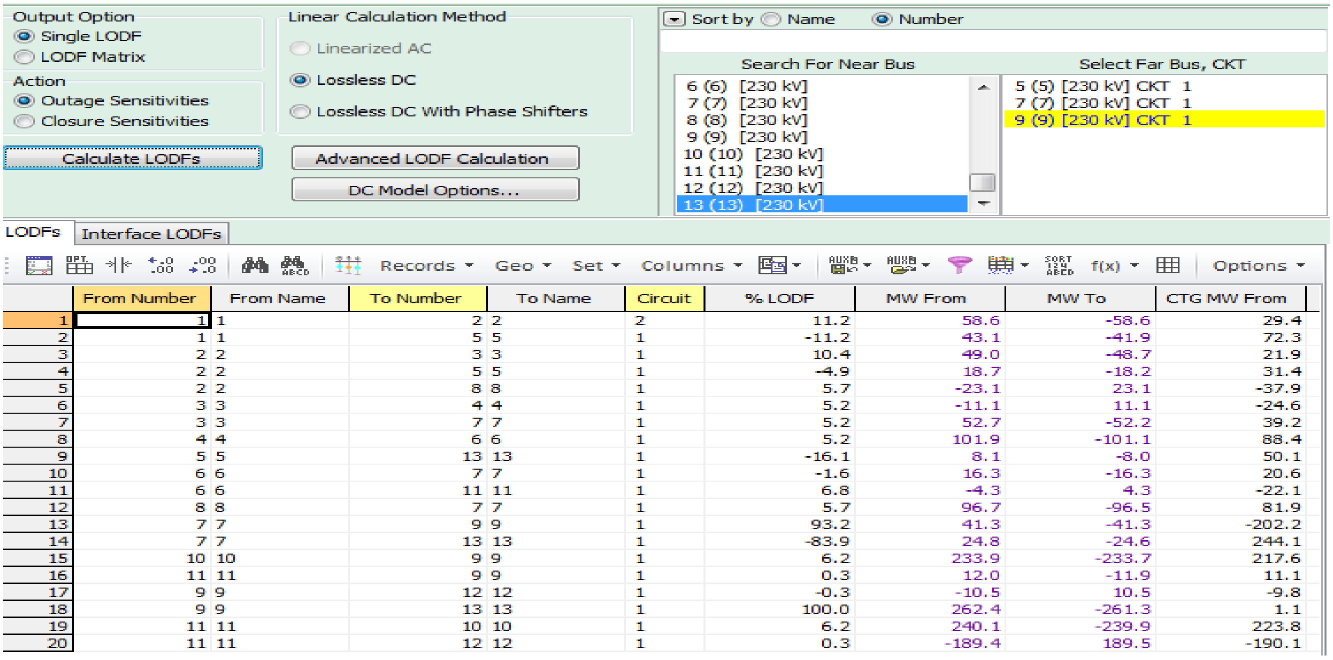
Lines are ranked in accordance with their sensitivity (% LODF) due to Sebeta to Kaliti line outage. The line has the most negative % LODF takes the first rank. Then, depending upon their rank the D-FACT devices are inserted on the most sensitive one (most negative %LODF) line.

DSSC Specification Calculation and Placement

The following steps have been considered in designing and sizing of the device:

1) Calculating line outage sensitivity (% LODF) and selecting the transmission line with the most negative % LODF. As Table 2 shows, Gefersa to Kaliti transmission line (7 to 13) is with the most negative % LODF.
2) The line inductance is 141881.25μH;
3) Percentage of maximum line impedance compensation specified is 80%;
4) Available impedance in DSSC to be injected: $X_{injected}$ = 0.8 * 141881.25μH= 113505 μH;

Table 2. LODF for line outage



	From Number	From Name	To Number	To Name	Circuit	% LODF	MW From	MW To	CTG MW From
1	1	1	2	2	2	11.2	58.6	-58.6	29.4
2	1	1	5	5	1	-11.2	43.1	-41.9	72.3
3	2	2	3	3	1	10.4	49.0	-48.7	21.9
4	2	2	5	5	1	-4.9	18.7	-18.2	31.4
5	2	2	8	8	1	5.7	-23.1	23.1	-37.9
6	3	3	4	4	1	5.2	-11.1	11.1	-24.6
7	3	3	7	7	1	5.2	52.7	-52.2	39.2
8	4	4	6	6	1	5.2	101.9	-101.1	88.4
9	5	5	13	13	1	-16.1	8.1	-8.0	50.1
10	6	6	7	7	1	-1.6	16.3	-16.3	20.6
11	6	6	11	11	1	6.8	-4.3	4.3	-22.1
12	8	8	7	7	1	5.7	96.7	-96.5	81.9
13	7	7	9	9	1	93.2	41.3	-41.3	-202.2
14	7	7	13	13	1	-83.9	24.8	-24.6	244.1
15	10	10	9	9	1	6.2	233.9	-233.7	217.6
16	11	11	9	9	1	0.3	12.0	-11.9	11.1
17	9	9	12	12	1	-0.3	-10.5	10.5	-9.8
18	9	9	13	13	1	100.0	262.4	-261.3	1.1
19	11	11	10	10	1	6.2	240.1	-239.9	223.8
20	11	11	12	12	1	0.3	-189.4	189.5	-190.1

5) Available $X_{injected}$ per module = 47 μH;
6) Total No. DSSC needed = ($X_{injected}$) / (Avail $X_{injected}$ per module)
   $=113505\mu H/(47\ \mu H/module)$
   = 2415 modules
7) Determining transmission line rated current, present and emergency state current flow through the targeted transmission line.
   $I_{thermal}$ = 627.55A, $I_{present}$ = 63.9A,
   $I_{emergency}$ = 652.652A;
8) Determining the triggering current (I_0) and maximum limit current (I_{lim}):
   % for I_0 setting = $I_{present}/I_{thermal}$ = 10.2 %, then
   $I_0 \geq$ 10 % of $I_{thermal}$ = 64A;
   % for I_{lim} setting = $I_{emergency}$ / $I_{thermal}$ = 104%,
   Then $I_{lim} \geq I_{thermal}$ = 652.652A;
9) Rated Current after DSSC devices inserted is 593.33A.
   Therefore, 593.33A $\leq I_{rated}$ = 627.55A.
   So, the Gefersa to Kaliti transmission line can withstand during Sebeta to Kaliti transmission line congestion.
10) From step 9, it indirectly proves that real power flow when DSSC inserted in targeted transmission line while the system is in emergency state is less or equal to rated real power flow in normal state.
    $P_{rated} = \sqrt{3}*V_{rated}*I_{rated}$ = 237.5 MW
    $P_{rated\text{-}after\text{-}DSSC\text{-}inserted}$ = 224.6 MW $\leq$ 237.5 MW
11) Check. 224.6 MW $\leq$ 237.5 MW, so it is OK!

Hence, the most sensitive line is Gefersa to Kaliti about -83%. These D-FACT devices inject magnetizing impedance value of 0.08pu. After the D-FACTS devices get inserted into a sensitive transmission line, line loading gets reduced from 104% to 95%. Now, as long as the line loading is below 100%, the system can withstand and able to serve.

Therefore, the D-FACT device selection is depending upon the present current flow at normal state and the current flow at emergency state. After D-FACT is inserted, the current passing through the line must be less than or equal to line rated current.

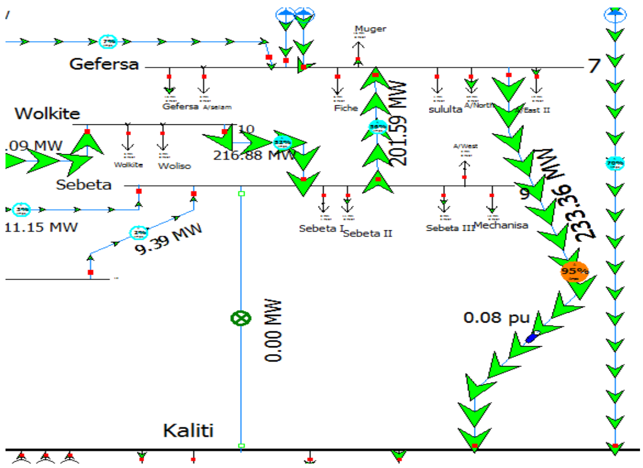


Fig. 7. After D-FACTS devices inserted

Table 3. MW flow and percentage loadings

Node to Node	Normal State		Emergency State		After DFACT Inserted	
	MW	MVA	MW	MVA	MW	MVA
Gefersa to Kaliti	4.7	10	258	104	233	95

Table 4. Setting of D-FACTS devices

X_{pe}	I_o% of $I_{thermal}$	I_{lim}% of $I_{thermal}$	Max % of	X_{inj}	Num	I_o (A)	I_{lim} (A)
47	10	104	80	235	2415	62.8	652.7

Other Cases

Outages of the other transmission lines have been tested one by one, but MVA limit violation has not been observed. But it is difficult to conclude at there is no transmission line MVA limit violation since load demand increases forever. As the time goes on the transmission line overloading also increases in proportion to load demand.

4. Result and Discussion

At normal state the percent MVA loading and MW flow of the transmission line from Sebeta to Kaliti is higher than the others. It is about 73% MVA loading and 262.39 MW respectively.

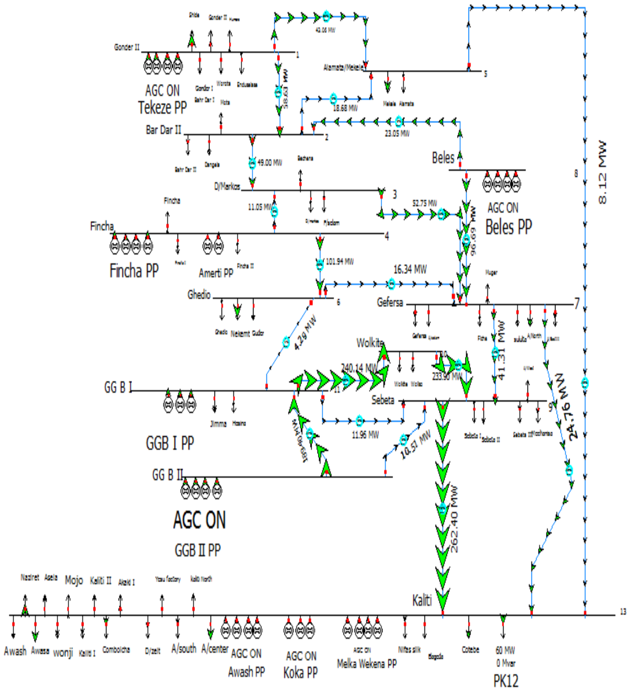


Fig. 8. Overall simulation result in normal state

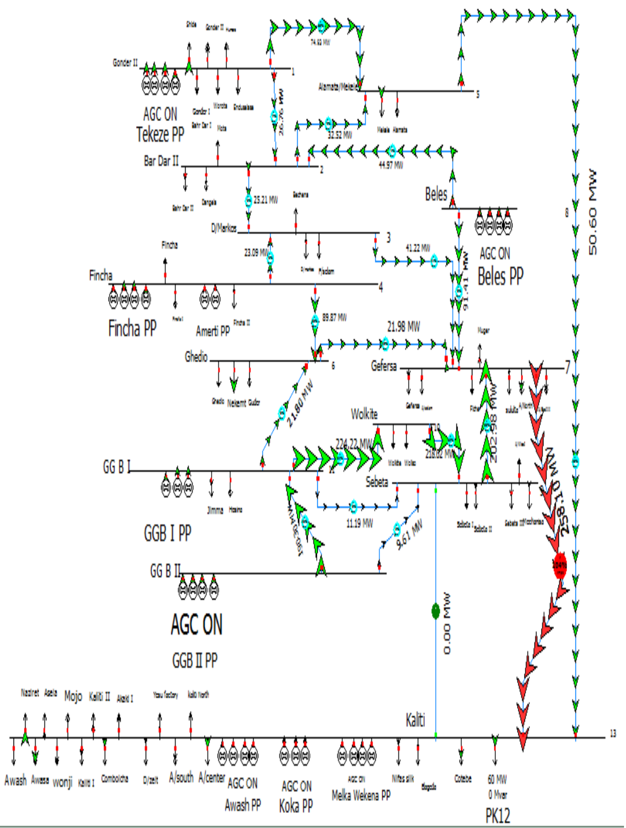


Fig. 9. Simulation result at emergency state

Both %MVA loading and MW flow of each line show at different states due to Sebeta to Kaliti line outage in Table 5 below.

The outage of Sebeta to Kaliti transmission line is not only cause overloading on Gefersa to Kaliti but also disturb all other lines in the network by increasing the percentage of loading and MW flow even though lines did not get overloaded. This assures that during the emergency of transmission line outage, both MVA percent loading and MW flows fluctuate unexpectedly.

When Sebeta to Kaliti line outage occur from the network due to some emergency cases, Gefersa to Kaliti line goes out by protective devices since it is running to be beyond its MVA limit. Consequently, the cascaded outage of Sebeta to Kaliti and Gefersa to Kaliti transmission lines, as it discussed above, it leads the network to the total system blackout, see fig.10.

When D-FACTS device inserted into the Gefersa to Kaliti line, according to the % LODF calculated, these devices reduce the percentage of loading and the megawatt flow of the Gefersa to Kaliti line by injecting magnetizing impedance about a value of 0.08pu.

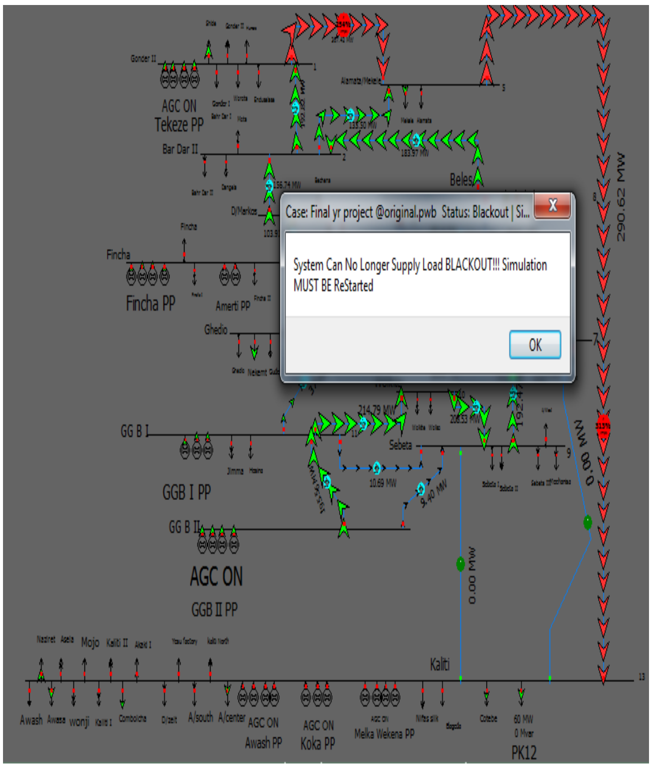


Fig. 10. Overall simulation result for cascaded outage of the two transmission lines

It reduce about 9% of MVA loading and 24.7 MW flow, which results in avoiding the transmission line from being overloaded and enable it to give service though it is still in warning i.e. about 95%.

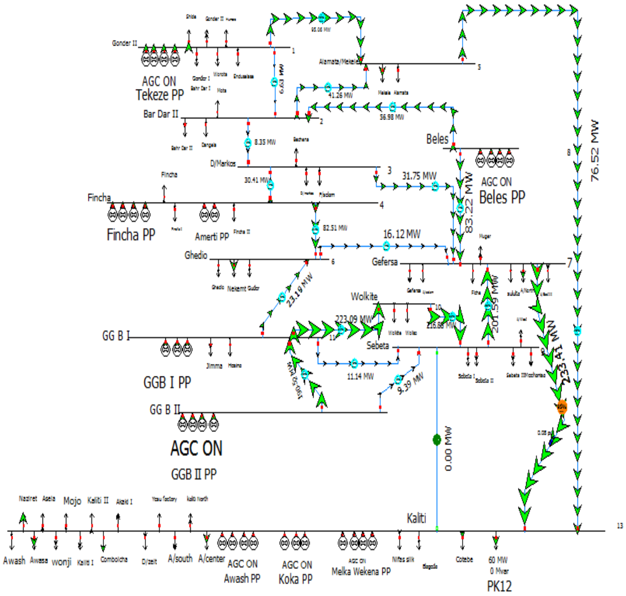


Fig. 11. Overall simulation result in emergency state when D-FACTS devices are inserted

Table 5. Percent MVA loading and MW flow of each transmission line at different states

Node to Node	Normal State		Emergency State		After D-Facts Insert	
	MW	MVA (%)	MW	MVA (%)	MW	MVA (%)
Gondar II to B/Dar II	58.63	15	26.76	7	6.63	2
B/Dar II to D/Mar	49	12	25.21	6	8.35	2
D/Mar to Fincha	11.05	3	23.09	6	30.45	7
Fincha to Ghedio	101.9	26	89.87	23	82.51	21
Ghedio to GGB I	4.29	1	21.8	6	23.19	6
GGB I to GGB II	189.4	17	190.3	16	190.5	16
Gondar II to Alemata	43.1	36	74.93	63	95.1	79
B/Dar II to Alemata	18.7	5	32.52	9	41.3	12
Alemata to Kaliti	8.1	10	50.6	46	76.5	70
Beles to B/Dar II	23.0	2	44.97	4	56.9	5
Beles to Gefersa	96.7	8	91.41	8	83.2	7
Wolkite to GGB I	240.1	58	224.2	54	223	54
Ghedio to Gefersa	16.34	8	21.98	10	16.1	7
Wolkite to sebeta	233.9	56	218.0	52	216.8	52
Sebeta to GGB II	10.5	3	9.61	2	9.39	2
Gefersa to Sebeta	41.31	12	202.9	56	201.6	56
Sebeta to Kaliti	262.4	73	0	0	0	0
Gefersa to Kaliti	4.72	10	258.1	104	233.4	95

But it will withstand as long as MVA loading is below its rating and can give service so that total network reliability and security are assured.

5. Conclusion

230KV transmission line contingency analysis of Ethiopia's power network is very important for the security and reliability of the system, since it is the high voltage next to 400KV line. The contingency occurs due to the outage of a single line in the network and it causes overloading on the other line. This overloading of a line may bring insulation failure and disturbance in all systems. To overcome this problem D- FACTS devices are the most preferable, efficient, cheap and applicable technology.

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