Effect of Contingency on Available Transfer Capability of Nigerian 330-kV Network

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Abstract

The transfer capability evaluation requires the consideration of various pre- and post-system contingencies to ascertain network security and the reliability of power systems. In this paper, the effects of single line (N-1) outage contingency and simultaneous transfer were considered in Nigerian 330-kV network. The results show that a single line outage not only lowers the available transfer capability (ATC) but can result in an infeasible operating condition (system collapse) of the Nigerian 330-kV power grid. Moreover, an additional source area results in higher transfer capability.

Keywords*: Line outage, simultaneous transfer, power system, single line outage, system collapse.*

1. Introduction

Typically, the transmission system (or the grid) refers to the high-voltage, networked system of transmission lines and transformers. Transfer of bulk electrical power between areas over long distances is preferred in order to have a reliable and economical electrical power supply. For example, electric power generated can be transferred to load centers via the high voltage transmission system (Dobson *et al*. 2001). A transmission element is, however, limited in capacity to transfer power, hence the distinction between capacity and capability (Sadiq and Nwohu 2013). In power systems planning and operation, unpredictable events such as line outage, loss of load or generator and control action due to transient condition is termed as contingency and may often be caused by line outage in the system which could result in system instability (Subramani *et al*. 2012). The investigation of the effects of contingency on line power flows, bus voltages and the stability of the remaining system (post-contingency) represents an important tool to study the effect of outages on the power system security during planning and operation.

Contingencies referring to disturbances such as transmission element outages or generator outages may cause sudden and large changes in both the configuration and the state (parameters) of the system. Contingencies may result in severe violations of the system operating constraints. Consequently, planning for contingencies is an important aspect of the secure power grid operation in the presence of emerging Nigerian power market deregulation.

The North American Electric Reliability Council (NERC) in 1995 reviewed its reference document on transfer capability in order to provide a framework and clarifications on the requirements for transfer capability computations. First contingency total transfer capability (FCTTC) is defined as first contingency incremental transfer capability (FCITC) plus normal base power transfers. FCITC is the amount of electric power incremental above the base case within acceptable constrained limitation ranges such that:

- Pre-contingency operating procedures allow all facility loading within normal ratings.
- The systems return to stability after any disturbances, like single line (*N*-1) outage.

- Post-contingency systems have all the facility within acceptable emergency loading limits.

The term total transfer capability (TTC) is equivalent to FCTTC while FCITC is now termed available transfer capability (ATC) (Sauer 1997). An understanding of the effects of contingency on the transfer capability of a transmission interface can be critical for both the system operator and the market participants. Certainly, disturbances and discrete events such as line outage and simultaneous transactions can affect the transfer capability (Gravener and Nwankpa 1999). Moreover, transfer between neighboring areas can cause power flows through the entire transmission network, and when another area is also engaged in loading its own transaction at the same time with the power flows, in reality the resultant simultaneous transfers can offset each other with often an unknown effect on the transfer capability. Consequently, the transfer capability is quantified by considering the effects of contingencies. In general, it is much easier to monitor the normal state power flows across an interface than to monitor the transfer capability of individual lines under normal and contingency states. Therefore, the transfer capability is dependent on the line outage contingencies considered, hence the contingencies have to be taken into consideration in practice (Gan *et al*. 2003; Othman *et al*. 2005, 2006).

In a single line (*N*-1) outage contingency procedure, a model of a single equipment failure event, that is one line or one generator outage, or multiple equipment failure events, that is two transmission lines or a transmission line and a generator, are simulated one after another in a sequence until all credible outages have been studied. For each outage tested, the contingency analysis procedure checks all power flows and voltage levels in the network against their respective limits (Mohamed *et al*. 2012; Milano *et al*. 2005).

In this paper, single line (*N*-1) outage contingency and simultaneous power transfer were considered in the case study of Nigerian 330-kV network.

2. Materials and Methods

2.1 The Nigerian 330-kV Network

The Nigerian 330-kV voltage level heretofore is referred to as the Nigerian grid. In power system analysis toolbox (PSAT) environment, the Nigerian grid is a power network of 32 buses, 27 transmission lines and 7 generating stations. The installed generating capacity of the Nigerian grid is 7,461 MW including hydro-resources and gas-fired (thermal) power stations. The Nigerian grid is made up of 5,523.8 km of 330-kV transmission lines and 32 330/132-kV substations with total installed transformation capacity of 7,688 MVA (equivalent to 6,534.8 MW). The average available capacity on 330/132 kV is 7,364 MVA which is about 95.8% of the installed capacity (Eseosa and Odiase 2012; Labo 2010). The Nigerian grid system considered in this paper is zoned into four geographical areas in conformity with the control structure of the electric utility, the Power Holding Company of Nigeria (PHCN). Table 1 gives the location of the seven power generating station and their respective installed capacity. A detail of the Nigerian 330-kV network is given in Sadiq and Nwohu (2013).

2.2 ATC Evaluation Method

The available transfer capability (ATC) evaluation method adopted in this paper is based on the hybridized continuous-repeated power flow structure.

Table 1. Electricity power stations of the Nigerian power grid (Sadiq and Nwohu 2013).

Power Station	Egbin	Sapele	Afam	Delta	Kainji	Shiroro	Jebba
Type/Fuel Used	Gas	Thermal	Thermal	Thermal	Hydro	Hydro	Hydro
Installed Capacity (MW)	1,320	1,020	969.6	912	760	600	578.4

The hybridized continuation-repeated power flow implements power transfers by increasing complex load with uniform power factor at every load bus in a sink area with increase in real power injection at generator buses in the source area at incremental steps up to a binding security limit, above which system security is compromised. The proposed algorithm is implemented in PSAT. The ATC is calculated using Eq. (1) (Ou and Singh 2002):

$$ATC = \sum_{i \in \sin k} P_L^i(\lambda_{\max}) - \sum_{i \in \sin k} P_L^{i_0} . \qquad (1)$$

2.3 Single Line (*N*-1) Outage Contingency

The single line outage (*N*-1) criterion is an important part of system security evaluation. In this paper, due to the radial topology of the Nigerian grid, tie line contingencies were not considered as outage of lines connecting the areas will result in no physical path between areas. In particular, a tie line between transmission substation (TS) Bus 3_Jebba (TS) to Bus 7_Oshogbo is critical for transaction from/to area 1. In addition, lines terminating only at a load bus and generator transformer outages are not considered as these contingencies lead to loss of load or generator outage, respectively (Sadiq and Nwohu 2013).

2.4 Simultaneous Inter-Area Power Transfer

In the presence of deregulation, multiple bilateral/multilateral transactions have become a reality as may be dictated by the power demand and the needs to meet generation reliability requirements. Various simultaneous transactions are feasible as presented in Hamoud (2000) and Wu (2007). The simultaneous inter-area power transfer considered here is an additional source area power transfer implemented on the existing source area, a contingency which may result in a deregulated power market to complement an existing contractual bilateral/multilateral transaction, the aim of which is to supply the short-fall in transfer capability resulting from a generator outage in the existing source area.

3. Results and Discussion

3.1 Effect of Single line (*N*-1) Outage on ATC

Table 2 gives the inter-area ATC computed values of Nigerian 330-kV network before contingency consideration while Table 3 gives the contingency ATC values, line outage considered and the limitations to each transfer direction. The void in Table 3 implies an infeasible operating condition. It is observed that single line outage generally results in lower ATC values. As seen from Table 2, the ATC computed value from area 1 to area 2 without (*N*-1) line outage contingency is 121 MW, and with line outage from Bus 7 to Bus 9 the ATC value decreased to 1.7 MW. Consequently, blackout and total system collapse could result from single line outage, particularly, line outage involving Bus 7_Oshogbo to Bus 9_Ayede, Bus 7_Oshogbo to Bus 29_Ikeja west, high tension (HT) Bus 25_Sapele (HT) to Bus 2_Benin (TS) and Bus 29_Ikeja west to Bus 2_Benin (TS) as various inter-area transfers result in an infeasible ATC.

3.2 Effect of Simultaneous Inter-Area Transfer on ATC

Table 4 shows the simultaneous inter-area transfers. Each transfer involves two source areas supplying the increase in load in a sink area.

Table 2. Inter-area ATC values of Nigerian grid.

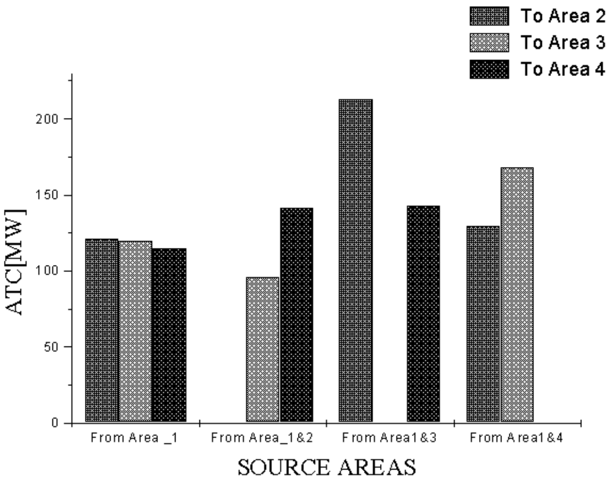
Inter-Area Transfers (MW)					
Source/ Sink Area		Source Areas			
		Area 1	Area 2	Area 3	Area 4
Sink Areas	Area 1	Void	2.61	167.26	6.58
	Area 2	121.43	Void	213.30	7.01
	Area 3	120.00	3.28	Void	6.59
	Area 4	114.69	4.00	309.56	Void

Table 3. Contingency ATC computed values of Nigerian Grid.

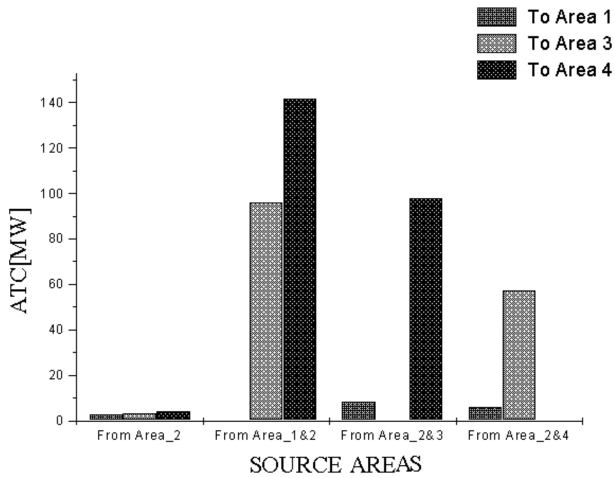
Inter-Area (*N*-1) Contingency					
Transactions		Line Outage		ATC (MW)	Limitations
From	To				
Area 1	Area 2	Bus 7	Bus 9	1.7	Bus 16 [Qg_max = 450]
		Bus 7	Bus 29	19.5	Bus 16 [Qg_max = 450]
		Bus 9	Bus 29	86.2	Bus 16 [Qg_max = 450]
Area 1	Area 3	Bus 7	Bus 29	66.5	Bus 16 [Qg_max = 450]
		Bus 7	Bus 2	114	Bus 3 TO Bus 7
		Bus 29	Bus 2	13.6	Bus 16 [Qg_max = 450]
Area 1	Area 4	Bus 7	Bus 29	63.4	Bus 16 [Qg_max = 450]
		Bus 7	Bus 2	109	Bus 3 TO Bus 7
		Bus 29	Bus 2	11.9	Bus 16 [Qg_max = 450]
Area 3	Area 1	Bus 24	Bus 2	148	Bus 25 TO Bus 2
		Bus 25	Bus 2	142	Bus 24 TO Bus 2
		Bus 7	Bus 29	165	Bus 4 [V_min < 297]
		Bus 7	Bus 2	164	Bus 4 [V_min < 297]
		Bus 29	Bus 2	6.68	Bus 16 [Qg_max = 450]
Area 3	Area 2	Bus 24	Bus 2	160	Bus 25 TO Bus 2
		Bus 25	Bus 2	149	Bus 24 TO Bus 2
		Bus 29	Bus 2	1.01	Bus 16 [Qg_max = 450]
		Bus 7	Bus 2	170	Bus 16 [Qg_max = 450]
Area 3	Area 4	Bus 24	Bus 2	159	Bus 25 TO Bus 2
		Bus 25	Bus 2	150	Bus 24 TO Bus 2
Area 2	Area 1	Bus 7	Bus 9	Void	Bus 15 TO Bus 29
		Bus 7	Bus 29	Void	Bus 15 TO Bus 29
		Bus 9	Bus 29	Void	Bus 15 TO Bus 29
Area 2	Area 3	Bus 24	Bus 2	2.28	Bus 15 TO Bus 29
		Bus 25	Bus 2	Void	Bus 15 TO Bus 29
		Bus 29	Bus 2	Void	Bus 16 [Qg_max = 450]
		Bus 29	Bus 2	Void	Bus 16 [Qg_max = 450]
		Bus 7	Bus 2	2.11	Bus 15 TO Bus 29
Area 2	Area 4	Bus 7	Bus 2	1.46	Bus 15 TO Bus 29
		Bus 29	Bus 2	Void	Bus 16 [Qg_max = 450]
		Bus 7	Bus 29	Void	Bus 15 TO Bus 29
Area 4	Area 1	Bus 7	Bus 29	5.37	Bus 22 TO Bus 21
		Bus 7	Bus 2	5.48	Bus 22 TO Bus 21
		Bus 29	Bus 2	Void	Bus 22 TO Bus 21
Area 4	Area 2	Bus 7	Bus 2	5.51	Bus 22 TO Bus 21
		Bus 29	Bus 2	Void	Bus 22 TO Bus 21
		Bus 7	Bus 29	5.61	Bus 22 (PS) TO Bus 21
Area 4	Area 3	Bus 24	Bus 2	5.73	Bus 22 (PS) TO Bus 21
		Bus 25	Bus 2	3.27	Bus 22 (PS) TO Bus 21

Table 4. Simultaneous inter-area ATC values of Nigerian grid.

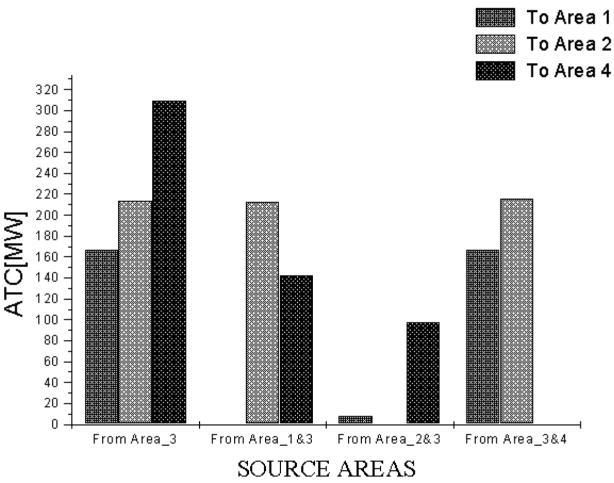
Simultaneous Inter-Area Transfers (MW)							
Sources/Sink Area		Source Areas					
		Area 1&2	Area 1&3	Area 1&4	Area 2&3	Area 2&4	Area 3&4
Sink Areas	Area 1	Void	Void	Void	8.31	5.92	167.28
	Area 2	Void	213.04	129.84	Void	Void	215.78
	Area 3	95.83	Void	168.17	Void	57.11	Void
	Area 4	141.76	142.96	Void	97.84	Void	Void



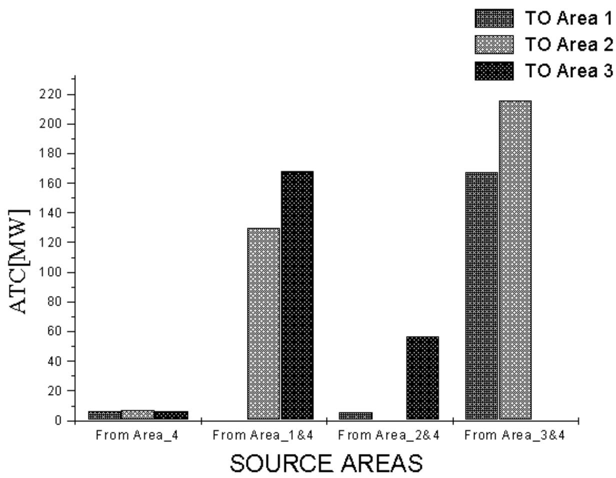
(a) EST on area 1 ATC computed values.



(b) EST on area 2 ATC computed values.



(c) EST on area 3 ATC computed values.



(d) EST on area 4 ATC computed values.

Fig. 1. Effect of simultaneous transaction (EST).

Figure 1 shows the effect of simultaneous inter-area power transfer on inter-area ATC computed values of Nigerian grid. It is observed that different areas have different effect on inter-area ATC values.

It can be deduced and depicted clearly in Figs. 1(a), (b) and (d) that an additional source area could result in higher transfer capability with exception of Fig. 1(c).

This abnormality in Fig. 1(c) could be attributed to the choice of slack generator. It is observed in Fig. 1(c) that only the transaction from area 2 to area 3 results in that abnormal condition.

With a change of slack generator from area 2 to area 3, the deduction becomes true as in Figs. 1(a), (b) and (d).

4. Conclusion

This paper uses hybridized continuous-repeated power flow structure for the assessment of inter-area available transfer capability of Nigerian 330-kV power grid. Normal and contingency ATCs were computed. Single line (N-1) outage criterion was implemented and the effects of simultaneous inter-area power transfers on ATC computed values were investigated. The result shows that (N-1) outage decreases the ATC and could also results in system collapse while the simultaneous inter-area transfer considered in this paper is an additional source area to complement a generator outage contingency in the existing transaction, hence the improvement of the results obtained from the ATC.

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