International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:9, No:5, 2015

Available Transmission Transfer Efficiency (ATTE) as an Index Measurement for Power Transmission Grid Performance

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***Abstract*—**Transmission system performance analysis is vital to proper planning and operations of power systems in the presence of deregulation. Key performance indicators (KPIs) are often used as measure of degree of performance. This paper gives a novel method to determine the transmission efficiency by evaluating the ratio of real power losses incurred from a specified transfer direction. Available Transmission Transfer Efficiency (ATTE) expresses the percentage of real power received resulting from inter-area available power transfer. The Tie line (Rated system path) performance is seen to differ from system wide (Network response) performance and ATTE values obtained are transfer direction specific. The required sending end quantities with specified receiving end ATC and the receiving end power circle diagram are obtained for the tie line analysis. The amount of real power loss load relative to the available transfer capability gives a measure of the transmission grid efficiency.

***Keywords*—**Available transfer capability, efficiency performance, real power, transmission system.

I. Introduction

IN modern power systems, Electrical power transmission network performance issues are important as they ensure the efficiency and security of generation, transmission and distribution thereby improving system wide reliability. Worldwide, utility companies and transmission system operators (TSO) are embracing deregulated framework in electrical power sector, thereby replacing traditional and centralized controlled grid structures, resulting into increase volume of bilateral transactions as well as operation and control of power systems in different ways. Hence, transmission grids are going to be operated closer to their limits. In the structure of deregulation, generation resources are often managed and operated by independent power producers while government adequately provide the facility of economical transaction between generators and consumers[1], [2].

The transmission network delivers large volumes of electricity from generation companies (Gencos) to load centers. Power system performance indicators have been used by utilities/Transmission system operators (TSO), this can be seen from various utility /TSO gathering to enhance power system performance by benchmarking parameters among participating utilities. Transmission system companies/ operators usually measure their achievements by using various types of qualitative and quantitative assessments. The quantitative indicators are commonly known as Key Performance Indicators (KPIs). Technical and financial KPIs can be used to measure the degree of achievements through monitoring of a number of performance indicators. The technical and financial KPIs may include: System Average Interruption Frequency Index (SAIF), System Average Interruption Duration Index (SAID), Energy Not Supplied (ENS), Average Interruption Time (AIT), Overhead Lines Maintenance Cost Index (OHLMCI) and Substation Maintenance Cost Index (SSMCI) [3], [4]. Technical performance of electricity transmission system is also quantified using measures such as system unavailability, quality of supply and energy lost. Energy lost measured in MWh is a transmission system incident occurrence such as element outages [5].

Electric power generation facilities in Nigeria has witness increase investment in order to meet increase in demand from consumers, without a proportionate investment in transmission; coupled with the difficulties in new transmission facility-acquiring new right of ways. Optimal and reliable operations of the existing transmission interconnections is sought after as an immediate solution; hence the need to assess transmission network performance for secure operation and planning as well as avoid congestion in an emerging Nigerian power sector deregulation. ATC and TTC are both indicators of transmission system performance [6].

Besides the need to accurately and rapidly assess the real time capabilities of the transmission grid in the restructuring of the electric power industry, knowledge and understanding (in the presence of deregulated power network) of power system network performance is vital in modern frame work of electricity supply. Output from transfer capability simulations provides general network steady state parameters since it is load a flow solution, bus voltage magnitude and phases, line real and reactive power flows, line losses and hence the resulting ATC is computed. This information is vital to ascertain the system performance within specified constraint imposed.

Nigerian 330kV transmission grid is characterized by

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various constraints and limitations ranging from voltage sags and instability, system collapse, slow expansion of transmission grid and transfer capability and capacity. These can be attributed to load growth and contingencies such as line outages and short falls in available generation capacity [7], [8].

Transfer Capability of transmission system is the amount of unutilized capability of the system at a given time and depends on factors such as Load demand, generation dispatch, network topology, simultaneous transfer, and power transfer between areas and the limits imposed on the transmission network due to thermal, voltage, generator reactive power and stability limits [9].Moreover, ATC is again the transmission limit for reserving and scheduling energy transactions in competitive electricity markets. Accurate evaluation of ATC is essential to maximize utilization of existing transmission grids while the transmission system is adequately secured [10].

Transfer capability computations have been approached by numerous methods this includes: Repeated power flow [11]–[13], Continuation power flow [14]–[17], optimal power flow [1], [11] and Sensitivity analysis [18]. In this paper, ATC computation uses Hybridized continuous-repeated power flow.

II. Line Model and Performance

A transmission line consists of conductors running over steel towers. These lines are in-between transformation stations to evacuate generated power from power stations to major load centers. The line inter-connects all power stations forming a solid network accessible by load centers. Transmission lines are usually represented on a per phase basis by their equivalent model with appropriate circuit parameters. Line to neutral voltages and one line (phase) current are used to express the terminal voltage, thus, allow a three phase system to be reduced to its equivalent single phase. Models adopted for transmission lines and used to calculate voltage, currents, and power flows are classified based on the length of the line [19]. The three models are outlined as follows:

A. Short line model: Lines less than 80km length or voltage not more than 69KV.
B. Medium line model: Lines above 80km long but less than 250km.
C. Long line model: Lines of length 250km and longer.

In [20] a short line model is documented. The expression for real and reactive power received over a lossless line $(B = jX', \theta_A = 0, \theta_B = 90$ and $A = Cos\beta l)$ model is given by (1) and (2) respectively. Where, β, δ and l are the phase constant, power angle and the line length respectively.

$$P_{R(3\phi)} = \frac{|V_{S(L-L)}||V_{R(L-L)}|}{X}\sin\delta \tag{1}$$

$$Q_{R(3\phi)} = \frac{|V_{S(L-L)}||V_{R(L-L)}|}{X}\cos\delta - \frac{|V_{R(L-L)}|^2}{X}\cos\beta l \tag{2}$$

Equation (1) shows that for a given system operating at constant voltage, the real power transferred is proportional to the sine of the power angle. Theoretically, the maximum power transferred under a stable steady state operating condition will occur for $\delta = 90^o$.

The mismatches between the sending and receiving end real and/or reactive power flows account for the line losses and expressed in (3) and (4):

$$P_{L(3\phi)} = P_{S(3\phi)} - P_{R(3\phi)} \tag{3}$$

$$Q_{L(3\phi)} = Q_{S(3\phi)} - Q_{R(3\phi)} \tag{4}$$

The plot of $Q_{R(3\phi)}$ versus $P_{R(3\phi)}$ for fixed line voltages and variable load angles is a circle; the locus of points obtained is called the receiving end power circle diagram. Such circles obtained with fixed receiving end voltages and varying sending end voltages are useful in the assessment of the performance characteristics of a transmission line [19].

III. Line Thermal Limit and Efficiency

Power handling ability of transmission line is limited by thermal loading limit and the stability limits. Thermal limits measurement (as available in manufacturer's data) establishes the current carrying capacity of a conductor, or the maximum amount of current that can flow through a transmission line or electrical equipment/facility over a given period (time) before a permanent damage is sustained or before public safety requirement is violated. Often express in Amperes, it is usual in Transfer Capability computation to also specify thermal limits of lines or transformers in MVA (Mega volts-amperes) or MW (Megawatts). Let the current-carrying capacity be denoted by I_thermal and then the thermal loading of a line in VA (or MVA) is given in (5).

$$S_{thermal} = 3 \times V_{\phi rated} \times I_{thermal} \tag{5}$$

The efficiency of a line engaged in power transfer is expressed in (6):

$$\eta = \frac{P_{R(3\phi)}}{P_{S(3\phi)}} \tag{6}$$

where $P_{R(3\varnothing)}$ and $P_{S(3\varnothing)}$ are the total real power at both receiving and sending ends of the transmission line respectively.

IV. Available Transmission Transfer Efficiency (ATTE)

Amount of power transferable over a given line above already committed uses is a measure of the Available transfer capability, often limited by the line thermal loading and hence a measure of transmission system performance. Various transfer cases with contingency consideration to simulate the resulting effects on power flows while considering thermal, voltage and generator reactive power limits gives an in-depth measure of transmission system performance in the presence of various power transfer scenarios considered. In this paper, tie line inter-area ATTE was also considered in the Nigerian 330kV transmission grid. The ratio of Available real power transfer at buying (receiving) and selling (sending) end is a measure of the transmission system efficiency for a given solved transfer case and direction. Consequently, in this paper, we introduce a novel concept to determine the transmission transfer efficiency by the term Available Transmission Transfer Efficiency (ATTE). Available transmission real power transfer efficiency is then defined as the ratio of the real power transfer at the receiving (buying) and sending (selling) end bus, as given in (7):

$$ATTE_{thermal} = \frac{P_{R(3\phi)}^{atc}}{P_{S(3\phi)}^{atc}} \times 100\% \tag{7}$$

where $ATTE_{thermal}$, is the Available Transmission Transfer efficiency, the transfer here is limited by transmission thermal loading and peculiar to the specified transfer case. $P_{R(3\varnothing)}^{atc}$, is the real power in MW at the receiving/sink end above base case up to binding security limit which is equivalent to the ATC and $P_{S(3\varnothing)}^{atc}$, is the real power in MW transferred at the sending/source end above base case up to binding security limit which is equivalent to the ATC plus losses incurred resulting from a transfer direction.

Therefore, by definition, the ATC evaluation method used in this paper gives ATC as in (8):

$$ATC = \sum_{i \in RA} P_L{}^i(\lambda_{\max}) - \sum_{i \in RA} P_L{}^{i0} \tag{8}$$

where $P_L{}^i(\lambda_{\max})$ is the i[th] bus real power load at the maximum loading parameter while $P_L{}^{i0}$ is the base case i[th] bus real power load. RA means receiving area.

Hence, $P_{R(3\varnothing)}^{atc}$ is equivalent to the ATC, while $P_{S(3\varnothing)}^{atc}$ is the ATC plus the real power losses associated with the transfer direction. Mathematically, we have that:

$$P_S^{atc} = P_R^{atc} + P_{Loss}^{atc} \text{ or } P_S^{atc} = ATC + P_{loss}^{atc} \tag{9}$$

$$\therefore\ ATTE = \frac{ATC}{ATC + P_{Loss}^{atc}} \times 100\% \text{ or}$$

$$\therefore\ ATTE = \frac{1}{1 + P_{loss}^{atc} / ATC} \times 100\% \tag{10}$$

The term P_{Loss}^{atc} / ATC, is the amount of loss load relative to the available transfer capability. Hence, the lower the value of P_{Loss}^{atc}, the higher will ATTE obtained.

In this paper, the Nigerian 330kV transmission grid is divided to four areas in conformity with the utility structure of Island, hence, inter-area Available transfer capability between the four identified areas are considered. The Nigerian grid modeled in PSAT environment is given in [8]

A. Area1 to Area2 Power Transfer

For line performance analysis, the transfer case is modeled such that at the maximum loading parameter which gives the Available Transfer capability, the load at the receiving end is the sum of all loads which is a member of the receiving area (i.e. area2). This is given in (11):

$$P_{L(\lambda_{\max})}^{RA} = \sum_{i \in RA} P_{L(\lambda_{\max})}^{i} \tag{11}$$

where $P_{L(\lambda_{\max})}^{RA}$, is the total real power load of the receiving area (RA) at the maximum loading parameter $\lambda_{\max}$ while $P_{L(\lambda_{\max})}^{i}$ is the i[th] bus real power load of the receiving area at $\lambda_{\max}$.

B. Bus3 (Jebba TS) to Bus7 (Oshogbo)

This tie line physically connects area1 to area2 only, without any physical path from area1 to other areas. Radial nature of the grid makes this tie line critical to the entire grid. However, transactions involving other areas (area2, area3 and area4) with area1is also considered to sufficiently measure the performance of the tie line under different transfer directions. The tie line is a three phase, 50Hz, 330kV transmission line of length 157km. The line parameters are R = 0.078Ω/km, C = 0.022218μF/km, L = 0.606mH/km. The line thermal rating is $I_{thermal}$ = 1360A [18]. Nominal π model is used in this paper for the tie line.

V. Results and Discussion

Inter-area transmission transfer efficiency of the Nigerian 330kV transmission grid was considered. Table I shows the Inter – Area ATTE values among the four areas of the Nigerian grid.

TABLE I
INTER-AREA TRANSMISSION TRANSFER EFFICIENCY OF NIGERIAN GRID

Inter-area Transmission Transfer Efficiency (%)					
		SOURCE AREAS			
Source/Sink Area		AREA 1	AREA 2	AREA 3	AREA 4
SINK AREAS	AREA 1	Void	93.88	90.89	91.64
	AREA 2	94.82	void	96.64	95.37
	AREA 3	99.91	97.91	void	97.05
	AREA 4	93.65	94.56	92.60	void

In Table II the transmission transfer efficiency of simultaneous inter-area transfer were presented. Two areas are considered as sources (sending area) among the four areas while a single sink (receiving) area different from the source areas is also chosen.

The radial nature of the Nigerian 330kV transmission grid prompted the reason for tie line transmission performance. Outage of these lines could cause undue risk to part or the entire system with black out or system collapse being the resulting effects [18].

TABLE II
SIMULTANEOUS INTER–AREA TRANSMISSION TRANSFER EFFICIENCY OF NIGERIAN GRID

Simultaneous Inter - Area Transmission Transfers Efficiency (%)							
		Source Areas					
Sources/Sink Area		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	94.53	95.17	91.68
	AREA 2	Void	97.07	95.52	Void	Void	97.24
	AREA 3	91.17	Void	98.99	Void	98.56	Void
	AREA 4	89.37	88.82	Void	95.23	Void	Void

The performance of the tie line is obtained under different inter-area Available transfer capability. The receiving end power circle diagram, voltage profile and line load ability curves are equally obtained for a specified inter-area power transfer which is the specified receiving end quantities.

Table III gives the total receiving area load of inter-area Available Transfer Capability of Nigerian 330kV grid. All receiving area loads are assumed to be at 0.9 PF lagging. For each transfer case in Table III, we determine the tie line performance. The tie line performance analysis is carried out with respect to each of the following,

- ✓ To calculate sending end quantities for specified receiving end MW and MVAR
- ✓ Obtain the receiving end power circle diagram
- ✓ Obtain load ability curve and voltage profile

TABLE III
REAL POWER LOAD (IN MW) AT THE RECEIVING AREA OF INTER-AREA TRANSFER OF NIGERIAN 330KV GRID

		SOURCE AREAS			
Source/Sink Area		AREA 1	AREA 2	AREA 3	AREA 4
SINK AREAS	AREA 1	void	881.41	1046.06	823.42
	AREA 2	1486.93	Void	1578.79	1372.51
	AREA 3	450.00	333.28	void	336.59
	AREA 4	606.49	495.79	801.36	Void

Table V gives the line performance quantities obtained for specified receiving end MW and MVar. Observe that the inter-area ATC from area1 to area2 results in higher transmission loss and hence unacceptably high percentage voltage regulation. Series and shunt capacitors can be used to compensate the line in other to improve the line performance. In Table VI a comparison is made between network response and rated sys path ATTE. The comparison is further depicted in Fig. 4. In transaction numbers 8 to 12, the rated system path method of ATC for those transfers is limited by both a generator transformer and a generator reactive power limit; this implies zero real power loss and hence zeros tie line loss ratio. The rated path ATTE is seen as too optimistic as clearly shown in Fig. 4.

At a power factor of 0.9 lagging, the Mvar at the receiving end are obtained and given in Table IV.

Fig. 1 gives the receiving end power circle diagram with fixed sending V_s end and varying receiving V_r end voltages. V_r varies from V_r to 1.3 V_r. The tie line voltage variation in practice is allowed up to $1.1V_r$.

TABLE IV
REACTIVE POWER LOAD (IN MVAR) AT THE RECEIVING AREA OF INTER-AREA TRANSFER OF NIGERIAN 330KV GRID

		SOURCE AREAS			
Source/Sink Area		AREA 1	AREA 2	AREA 3	AREA 4
SINK AREAS	AREA 1	Void	426.87	506.61	398.78
	AREA 2	720.12	void	764.61	664.71
	AREA 3	217.93	161.41	void	163.01
	AREA 4	293.72	240.11	388.10	void

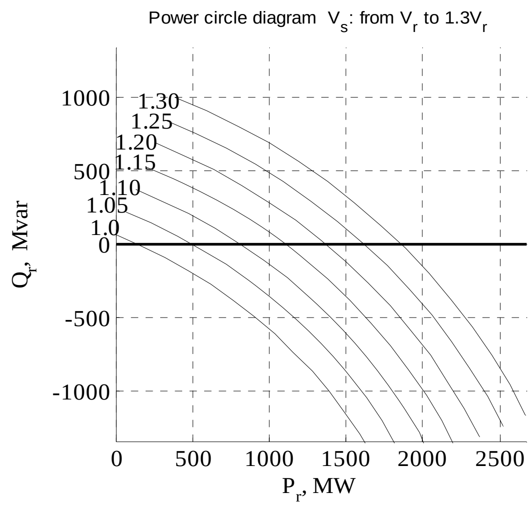

Fig. 1 Power circle diagram of tie line connecting area1 to area2

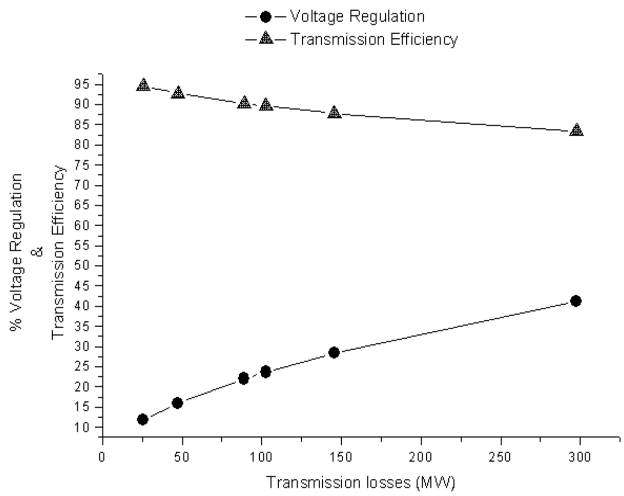

Fig. 2 Transmission Real power loss with respect to voltage regulation and efficiency

As shown in Fig. 2, it is observe that while Transmission efficiency decreases with increase in real power loss, percentage voltage regulation increases with increase in real power loss both resulting from inter-area power transfer.

Fig. 3 shows the voltage profile for length up to one eight of wavelength under various scenarios of no load, surge impedance level (SIL), short circuit condition and rated load conditions.

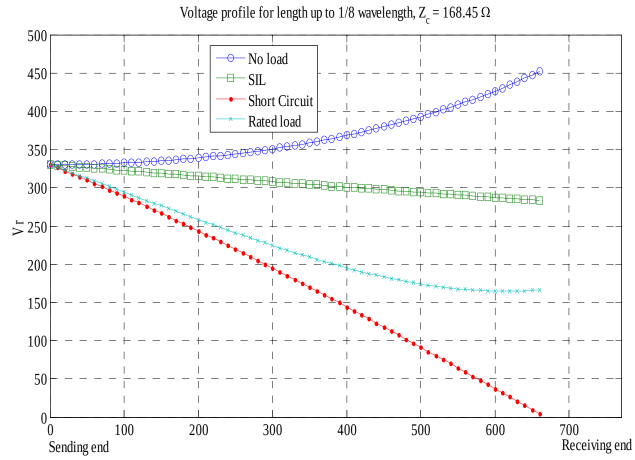

Fig. 3 Voltage profile of the tie line under various loading condition

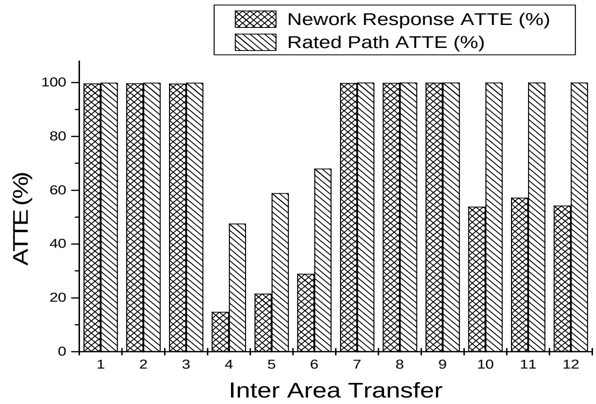

Fig. 4 Comparison between network response and rated system ATTE

TABLE V
TIE LINE PERFORMANCE FOR SPECIFIED RECEIVING END ATC (PR)

Transfer	Vr (Volts)	Vs (Volts)	Required Sending ANGLE	Pr (MW)	Ps (MW)	Ploss (MW)	Is (A)	Ir(A)	% Voltage Regulation	Efficiency (%)
Area1 to Area2	330	458.43	-25.84	1486.93	1784.61	297.68	2759.91	2890.48	41.23	83.32
Area1 To Area3	330	362.72	5.52	450.00	475.59	25.59	793.12	874.62	11.74	94.62
Area1 To Area4	330	376.56	7.05	606.49	654.01	47.52	1086.23	1178.97	16.00	92.73
Area2 To Area1	330	401.46	9.49	881.41	983.94	102.53	1606.64	1713.40	23.67	89.58
Area3 To Area1	330	416.69	10.81	1046.06	1191.57	145.51	1919.69	2033.46	28.37	87.78
Area4 To Area1	330	396.15	9.00	823.42	912.59	89.17	1496.56	1600.66	22.04	90.23

TABLE VI
COMPARISON BETWEEN NETWORK RESPONSE AND RATED SYSTEM ATTE VALUES

S/N	Transfer direction Source Area	Sink Area	ATC (MW)	Network Real power loss (MW)	Tie line real power loss	P_{Loss}^{atc}/ATC Network Loss Ratio	P_{Loss}^{atc}/ATC Tie line ratio	Network response ATTE (%)	Rated System Path ATTE (%)
1	Area1	Area2	121.43	53.37	11.82	0.44	0.10	99.64	99.92
2	Area1	Area3	120.00	46.78	11.66	0.39	0.10	99.68	99.92
3	Area1	Area4	114.69	54.52	11.67	0.48	0.10	99.59	99.91
4	Area2	Area1	2.61	39.25	7.50	15.04	2.87	14.79	47.60
5	Area2	Area3	3.28	39.15	7.51	11.94	2.29	21.56	58.89
6	Area2	Area4	4.00	39.31	7.53	9.83	1.88	28.93	68.01
7	Area3	Area1	167.26	53.96	7.93	0.32	0.05	99.81	99.97
8	Area3	Area2	213.30	44.61	0.00	0.21	0.00	99.90	100.00
9	Area3	Area4	309.56	62.00	0.00	0.20	0.00	99.94	100.00
10	Area4	Area1	6.58	37.01	0.00	5.62	0.00	53.91	100.00
11	Area4	Area2	7.01	36.75	0.00	5.24	0.00	57.21	100.00
12	Area4	Area3	6.59	36.61	0.00	5.56	0.00	54.26	100.00

In Fig. 4, a comparison is made between rated system path method of ATTE and network response method, the Tie line (Rated system path) performance is seen to differ from system wide (Network response) performance, hence the rated system path method provide a too optimistic ATTE. Fig. 5 shows the tie line load ability curve under three limits: practical line load ability, theoretical stability limit and the thermal limit, all for up to one fourth of the wavelength. SIL obtained is 659.39MW at 30^0.

VI. CONCLUSION

In this paper, Available Transmission Transfer efficiency (ATTE) is used to measure the performance of a tie line and the Nigerian 330kV transmission grid through inter-area transfer implementation, thereby taking into account the real power losses resulting from inter-area transfer capability. A plot of reactive power against the real power at the receiving end gives the power circle diagram. The results shows that while Transmission efficiency decreases with increase in real power loss, percentage voltage regulation increases with increase in real power loss both resulting from inter-area power transfer. It is therefore concluded that ATTE is dependent on direction of transfer, method of ATC and transmission losses incurred due to a transfer direction.

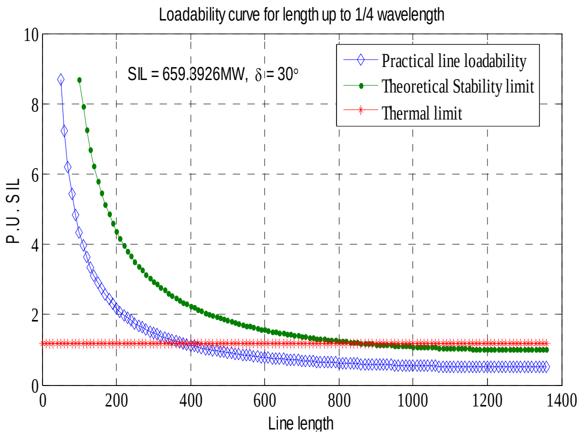

Fig. 5 Tie line load ability curve for Area 1 TO Area 2 Transfer (Jebba TS to Oshogbo)

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