Sensitivity-based approach for evaluation and enhancement of available transfer capability using FACTS devices

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ABSTRACT

Available transfer capability (ATC) plays an important role in the reliable and secure power system operation. It measures the transfer capability available in the transmission system for further trading over and above existing commitments without violating the system limits. The increased demand for electric power in recent years due to increasing population, automation in industries, and use of electricity in transportation, and also the deregulation of power systems results in an overload of the transmission network and hence congestion in the system. Therefore, quick and accurate calculation of ATC and its enhancement is needed for secured and reliable operation. It is possible to enhance ATC by placing the flexible alternating current transmission systems (FACTS) devices of appropriate size and at optimal locations in the system. In this paper, a computationally efficient sensitivity-based approach for evaluation and enhancement of available transfer capability in the presence of of FACTS devices is presented. The developed approach is implemented on the IEEE 14 bus system.

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1. INTRODUCTION

The deregulation of the electrical power system resulted in many notable changes in the operation and control actions of the power network. With the increasing number of bilateral/multilateral transactions, the possibility of insufficient transmission capacity leads to network congestion. The operational and planning aspects to address an issue of network congestion initiate few challenges in the deregulated power industry. In such a situation, evaluation, and improvement of Available transfer capability (ATC) of the transmission system become the most important issue. The ATC indicates the ability of the transmission system to efficiently increase the power transfer for further commercial trading between two areas or points. An incorrect value of ATC results in inefficient use of the transmission network. Accordingly, the accurate and efficient method of ATC calculation is very much essential in today's power system framework.

According to the North American Electric Reliability Council (NERC) [1], the total transfer capability (TTC) of the transmission system is the largest amount of power that can be transferred between two areas or zones or buses that does not result in an overload of transmission lines, violations in voltage limits at system buses and/or any other system security problems [1]. Mathematically ATC is defined [2] as (1).

$$ATC = TTC - TRM - CBM - ETC \tag{1}$$

Here transmission reliability margin (TRM) is the transfer ability of the system required to ensure that the power system is secure during uncertainties. Also, capacity benefit margin (CBM) is the transfer capability reserved for load-serving systems to access generation reliability requirements. ETC is the existing transfer commitment.

In recent years researchers have proposed various methods for calculation and enhancement of ATC. Few authors in the literature have proposed continuous power flow (CPF) and repeated power flow (RPF) methods for the evaluation of ATC as they are mathematically simple [3]. However, these methods are more time-consuming [4]. The sensitivity factors-based fast computational methods using DC and AC power transfer distribution factors (PTDFs) [5], have been used by many researchers for evaluating ATC, the same approach can be further extended to compute ATC during outages by finding line outage and generator outage distribution factors (LODF, GODF). These techniques are faster compared to CPF and RPF methods [6], [7]. However, these are based on few assumptions. Some researchers have proposed optimization techniques such as the hybrid grey wolf flower pollination algorithm for the evaluation of ATC [8]. TLBO, Cuckoo search [9], gravitational search [10] and adaptive moth flame optimization [11] techniques are various optimization algorithms used to evaluate and enhance ATC in the presence of TCSC. The probabilistic approach of using sequential game theory is another approach for the evaluation of ATC which considers dynamic line rating [12]. Few authors have proposed a method to evaluate ATC by considering some typical uncertainties that are needed for planning of power system over a longer duration [13]. Minimization of real power losses and improvement in voltage profiles at all buses are considered as primary objectives by few researchers to enhance ATC in presence of FACTS [14].

Many researchers have discussed the importance of computating the correct value of ATC in the present system of deregulation quickly and enhancing the same using FACTS. An attempt is made in this paper also to evaluate the ATC at a faster rate with reduced computations using dominating PTDFs and the results are compared against those obtained using DCPTDF and RPF method. Also, sensitivity-based formula is employed for deciding the suitable location of FACTS to improve ATC. The proposed methodology is implemented on the IEEE 14 bus system.

2. ATC CALCULATION METHODS

As energy regulatory commissions has allowed for open access to the transmission network, large-scale power transactions between utilities have increased rapidly. Also, the transactions between areas and buses are continuously increasing as the power demand is increasing. Because of this the transmission network is highly congested and system limits are getting violated which results in the insecure operation of the power system. To assist the deregulated market participants to carry out bilateral transactions without affecting system security, the evaluation of ATC plays an important role. Different methods are proposed in the literature by researchers to calculate ATC. These methods are classified into four types; (a) repeated load flow (RPF) method, (b) linear approximation method, (c) optimal power flow (OPF) method, and (d) probabilistic approach.

2.1. Repeated power flow technique

In the RPF method, ATC is computed by carrying out load flow analysis repeatedly [15] until any of the system limits get violated. In this method, a combination of source and sink bus are chosen and real power injection is increased at the source bus and the equal amount of real power demand is increased at the sink bus in regular steps. The power flow analysis is performed and bus voltages, the line loadings are observed in every step. This process of repeated power flow analysis is continued until any line in the system reaches its maximum loading limit. The real power injection at the source bus for the last step is noted down. If P_{max} represents the power injection at the source bus when maximum limit is attained and P_{base} represents real power at the same bus for the base case, then ATC is calculated using (2).

$$ATC = P_{max} - P_{base} \tag{2}$$

2.2. Linear approximation method (LAM)

In LAM, the ATC of the system is obtained by computing sensitivity factors for the given network topology. The power transfer distribution factor (PTDF) is one factor used to find the incremental distribution of power flows through transmission lines corresponding to power transactions between two areas/busses/regions [16]. Two types of PTDF are defined for evaluation of the ATC of the system viz. AC PTDF and DC PTDF. In the AC PTDF method reactive power flows along with active power flows are considered in evaluation of ATC whereas in DC PTDF only active powers flows are considered. Though AC PTDF gives more accurate results as compared to DC PTDF, it is computationally complex and time consuming because of the execution of complete AC power flow for each generator outage contingency analysis. Therefore, DC PTDF method is more popularly used to calculate ATC.

2.2.1. DC PTDF method

PTDF for any particular line is defined as a fraction of the amount of transaction from seller area/bus to buyer area/bus that flows through a transmission line [17]. Symbolically, $PTDF_{ij,mn}$ is a fraction of a transaction from source bus ‘m’ to sink bus ‘n’ that flows through a transmission line from bus ‘i’ to bus ‘j’ and the formula for computing PTDF is given in (3).

$$PTDF_{ij,mn} = \frac{X_{im}-X_{jm}-X_{in}+X_{jn}}{x_{ij}} \quad (3)$$

In (3), x_{ij} is reactance of transmission line connecting the buses i and j. X_{im}, X_{jm}, X_{in} and X_{jn} are the elements of bus reactance matrix obtained from bus admittance matrix. Once the PTDF are calculated, total transfer capability (TTC) of a line connecting i-j is calculated using (4).

$$T_{ij,mn} = \begin{cases} \frac{P_{ij}^{max}-P_{ij}^{0}}{PTDF_{ij,mn}} & ; \quad PTDF_{ij,mn} > 0 \\ \frac{-P_{ij}^{max}-P_{ij}^{0}}{PTDF_{ij,mn}} & ; \; PTDF_{ij,mn} < 0 \\ \infty & ; \quad PTDF_{ij,mn} < 0 \end{cases} \quad (4)$$

In (4), P_{ij}^{max} is the thermal limit of line connecting bus i and j, P_{ij}^{0} is the base case power flow through a line connecting bus i and j. The line with minimum transfer capability is called as limiting branch which gives ATC of the system as given in (5).

$$ATC = \min\{T_{ij,mn}\} \quad (5)$$

2.2.2. Proposed approach using dominating PTDF

From the literature, it is observed that AC-PTDF and DC-PTDF methods are computationally more complex, especially in the case of large interconnected systems. It is because these methods necessitate the calculation of transfer capabilities for all transmission lines and then opting for the minimum of these as ATC [18]. This approach makes the whole process more complex and time-consuming. Also, when the power system operator is required to make a decision to allow participants in a deregulated market for power transaction quickly, it is difficult by these methods resulting in congestion in transmission lines. To avoid these problems, in this work a computationally efficient method using only dominating PTDF is proposed for evaluation of ATC. In this approach PTDFs are calculated for all lines and for all required transactions (seller-buyer pair), then their absolute values are noted down and 40% of the total lines with higher absolute PTDF are further considered for computation of ATC of a system. This approach is valid because, if lines having lower values of absolute PTDFs are taken in evaluating transfer capability, it results in very large value of TTC from equation (4). When lines with such low absolute PTDF are compared with others to choose the minimum, obviously it is discarded. Therefore, in the proposed method, for a given system topology and required pair of transactions dominating PTDFs are evaluated and stored as a standard data. At the time of evaluation of ATC, the power flow analysis is carried out and transfer capability is evaluated for only those lines having dominating PTDF and corresponding ATC is observed.

Steps involved in dominating PTDF approach:

Step 1. PTDFs are calculated using (3), dominating PTDF are noted down for a given system topology, also for possible bilateral transactions, and is made available for further use.

Step 2. Power flow analysis is carried out on the system during particular conditions and checked against the system constraints. Power flows through transmission lines are noted.

Step 3. Transfer capabilities are calculated using (4) for only those lines which are having higher PTDF as obtained in step (1).

Step 4. ATC for particular condition is obtained by choosing minimum value of transfer capability.

3. MODELING OF FACTS DEVICES

The FACTS is system/devices based on power electronic controllers with quick operation, are used to enhance the performance of transmission network by increasing the use of their capability [19]. There are various FACTS devices viz. static synchronous series compensator (SSSC), Unified power flow controller (UPFC), static var compensator (SVC), Thyristor controlled series compensator (TCSC), and Thyristor controlled phase angle regulator (TCPAR). are used in system for power flow control, voltage control, reactive power compensation, stability improvement, power quality improvement, power conditioning, flicker mitigation, interconnection of renewable and distributed generation and to increase the transmission capability. The use of TCSC and SVC to enhance ATC of the system is discussed in this paper.

3.1. Modeling of TCSC

A TCSC is thyristor-controlled capacitive reactance connected in series with the transmission line to provide continuous control of power flow over a wide range. A TCSC module consists of a series capacitor, C, in parallel with a thyristor-controlled reactor, Ls, as shown in Figure 1.

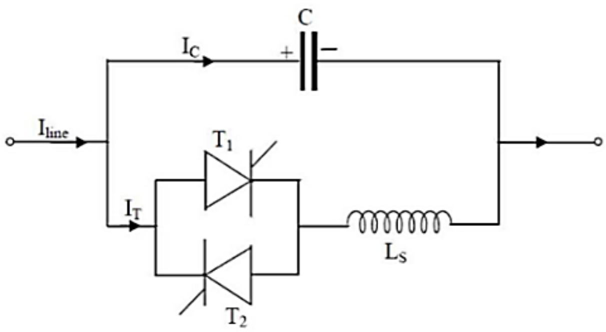

Figure 1. A TCSC module

The equivalent reactance of TCSC in terms of firing angle of thyristor α is given by (6).

$$X_{tcsc} = X_c - \frac{X^2{}_c}{(X_c - X_L)} \frac{2(\pi-\alpha)+\sin2(\pi-\alpha)}{\pi} + \frac{4X^2{}_c}{(X_c - X_l)} \frac{\cos^2(\pi-\alpha)}{(k^2-1)} \frac{(k\tan k(\pi-\alpha) - \tan(\pi-\alpha)}{\pi} \quad (6)$$

Here, $k = \sqrt{\frac{X_c}{X_L}}$, this model of TCSC is called as firing angle model. If X is the reactance of transmission line where TCSC is connected, the effective reactance of line after connection is obtained by using (7).

$$X_{eff} = X + X_{tcsc}. \quad (7)$$

3.2. Modeling of SVC

According to IEEE and CIGRE, static VAr compensator (SVC) is “a static VAr generator whose output is varied to maintain or control specific parameters of the electric power system, typically bus voltages by exchanging capacitive or inductive current” [20]. The main purpose of using SVC is to control voltage at weak buses in a network rapidly. SVC module shown in Figure 2 consists of a fixed capacitor (FC) and a thyristor-controlled reactor (TCR). This model of SVC is known as firing angle model as shown in Figure 2(a). A static capacitor/ reactor with variable susceptance Bsvc is equivalent to shunt compensator SVC which is known as susceptance model shown in Figure 2(b).

The equivalent susceptance of SVC in terms of firing angle of thyristor α is given by (8).

$$B_{svc} = \frac{1}{X_c X_L}\left[X_L - \frac{X_c}{\pi}(\pi - 2\alpha - \sin2\alpha)\right] \quad (8)$$

If V_k is the voltage at network connection bus, the reactive power generated by SVC is given by (9).

$$Q_{svc} = -B_{svc} V_k{}^2 \quad (9)$$

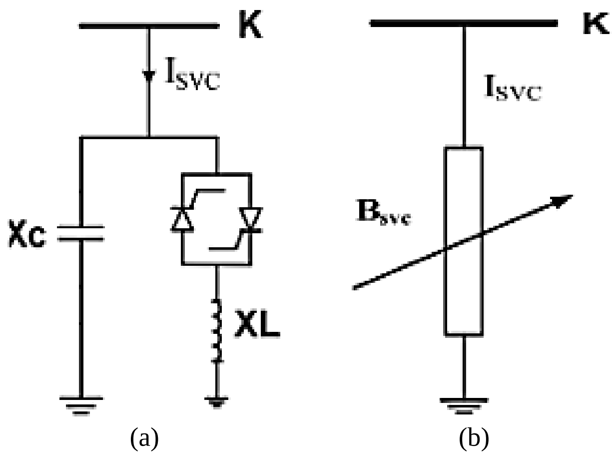

Figure 2. SVC model; (a) firing angle model and (b) equivalent susceptance model

3.3. Methodology to choose optimal location of TCSC

In order to change the parameters of existing transmission lines so as to increase their ATC and hence to avoid the setting up of new transmission lines, minimum number of FACTS devices need to be optimally located. In this work following sensitivity indices are used to find the correct location of FACTS devices to enhance ATC and to make overall system cost effective.

3.3.1. Real power flow performance index sensitivity

The real power flow performance index (PIP) is calculated by considering the real power flows [21] through the lines during line outages. This index is a good indicator of the real power flow security of the system. PIP is calculated by using (10).

$$\mathrm{PIP} = \sum_{m=1}^{n_l} \frac{w_m}{2n} \frac{P_{lm}}{P_{lmax}} \tag{10}$$

Here n_l is the total number of lines in the system, w_m is the non-negative weighting coefficient which is usually equal to 1. n is an exponent which is also taken as 1. P_{lm} is the active power flow through the line m. P_{lmax} is the rated capacity of the line m. PIP is calculated considering all line outages. The highest value of PIP indicates the possible location for placement of TCSC [22].

3.3.2. Real power flow sensitivity index (RPSI)

The sensitivity of real power flows P_{ij} through the line connecting buses i and j with respect to the parameters of TCSC are used to find the optimal location of TCSC in the system. RPSI factor concerning the control variable of TCSC is given by (11).

$$\mathrm{RPSI}_{ij} = \frac{\partial P_{ij}}{\partial X_{ij}} = \left[-V_i^2 + V_iV_j \cos\delta_{ij}\right] \frac{2*r_{ij}^2*x_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} + \left(V_iV_j\sin\delta_{ij}\right) * \frac{r_{ij}^2-x_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} \tag{11}$$

Here $X_{ij} = r_{ij} + jx_{ij}$ is the net reactance of line connected between bus i and j upon placing TCSC. V_i and V_j are the voltages at bus i and j respectively. And $\delta_{ij} = \delta_i - \delta_j$ where $\delta_i$and δ_j are phase angles at buses i and j respectively.

3.3.3. Total system real power loss sensitivity index (RLSI)

The sensitivity of real power losses P_{loss} of the system with respect to parameters of TCSC is another factor used to find the optimal location of TCSC in the system. RLSI factor concerning the control variable of TCSC is given by (12).

$$\mathrm{RLSI}_{ij} = \frac{\partial P_{loss}}{\partial X_{ij}} = \left[V_i^2 + V_j^2 - 2V_iV_j \cos\delta_{ij}\right] \frac{-2*r_{ij}^2*x_{ij}^2}{(r_{ij}^2+x_{ij}^2)^2} \tag{12}$$

3.3.4. Total system reactive power loss sensitivity (QLSI)

The sensitivity of reactive power losses Q_{loss} of the system with respect to the parameters of TCSC are also used to find the optimal location of TCSC in the system. QLSI factor with respect to the control variable of TCSC is given by (13).

$$QLSI_{ij} = \frac{\partial Q_{loss}}{\partial X_{ij}} = \left[V_i^2 + V_j^2 - 2V_iV_j \cos\delta_{ij}\right] \frac{r_{ij}^2 - x_{ij}^2}{\left(r_{ij}^2 + x_{ij}^2\right)^2} \quad (13)$$

Step-wise procedure to find the optimal location of TCSC:

Step 1. Read the system data and perform the load flow analysis on base case condition. Calculate the PIP index for the base case conditions.
Step 2. Perform load flow analysis with all line contingencies one by one and compute the corresponding PIP index.
Step 3. The line with the highest value of PIP is most critical contingency; hence lines with the higher value of PIP become possible locations for placement of TCSC.
Step 4. Load flow analysis is performed again by placing TCSC in those critical lines one after the other and corresponding sensitivity indices (RPSI, RLSI, and QLSI) are calculated.
Step 5. The line with the highest value of above-calculated indices is chosen as the optimal location of TCSC which results in maximum ATC.

3.4. Methodology to choose optimal location of SVC

In order to enhance the bus voltage profile and hence to improve the efficiency of transmission lines by reducing real power losses and enhancing the ATC, the appropriate size of SVC should be placed at the correct location (bus) in the system. As SVC is modeled as a reactive power generator at buses, it directly affects the voltage profile of the system. Therefore voltage benefit factor (VBF) [23] is calculated by placing SVC at every bus using (14).

$$VBF = \sum_{i=1}^{nb} \frac{V_{i_{with\ svc}} - V_{i_{without\ svc}}}{Q_{svc}} \quad (14)$$

Here, Q_{svc} is the amount of reactive power support from SVC when placed system's load buses, $V_{i_{with\ svc}}$ is the voltage at bus i when SVC is placed and $V_{i_{without\ svc}}$ is voltage without SVC. Once VBF is calculated by placing SVC at all load buses, the bus with the largest VBF is chosen as optimal location of SVC.

4. RESULTS AND DISCUSSION

In this study, the IEEE 14 bus system [24], consisting of of three PV buses and nine load buses along with two transformers and one shunt capacitor [25], is considered for ATC evaluation by both RPF and PTDF methods. Also, ATC is evaluated using dominating PTDF method for base case and different loading conditions. The enhanced values of ATC are obtained by placing FACTS devices at the optimal locations.

4.1. FACTS Devices considerations

- TCSC is assumed to provide 20% compensation, so that effective reactance of the line with reactance X_{line} after placement of TCSC will be $X_{eff} = X_{line} + 0.2*X_{line}$.
- SVC is assumed to have susceptance of -10.0006 S (L=55μH, C=20μF, α=0.8 rad, f=50Hz), so that reactive power support after placing SVC at bus with voltage V_k will be $Q_s = -10.0006*V_k^2$.

4.2. ATC results comparison using DC-PTDF, dominating PTDF and RPF methods for base case

ATC values are obtained for the IEEE 14 bus system using the DC-PTDF method using MATLAB, where in all PTDF values are calculated every time, and corresponding transfer capabilities are evaluated for all lines to obtain a minimum one as ATC and time taken for computation is noted down. Also, ATC values are obtained for the system using only dominating PTDFs using MATLAB, and time taken is noted. Here time for computation is noted down using the same PC with particular specifications and the time taken in both cases is compared. Finally, The ATC values obtained by these methods are validated using the RPF method using power world simulator.

It is observed from the Table 1 that ATC values obtained by using all PTDF and only dominating PTDF are same, but the time taken for computation is more in case if all PTDFs are used. Also, the ATC values obtained using RPF method from power world simulator is comparable with that of dominating PTDF method. Therefore, in this paper for all further analysis dominating PTDF method is used which is computationally efficient and accurate.

Table 1. ATC in MW using different methods and time taken for computation

Source Bus	Sink Bus	ATC in MW using different methods				
		DC PTDF		Dominating PTDF		RPF method
2	5	16.4877	Time taken in	16.4877	Time taken in	15
2	6	10.6660	seconds	10.6660	seconds	9
2	10	11.8711	is 0.001748	11.8711	is 0.000795	11
2	13	11.6591		11.6591		10
3	5	27.3312	Say T1	27.3312	0.45 *T1	25
3	6	10.9613		10.9613		8
3	10	11.6675		11.6675		12
3	13	12.0129		12.0129		14

4.3. Optimal location of TCSC

To find the optimal location of TCSC, sensitivity factors discussed earlier are calculated considering all line outages and are tabulated in Table 2. It is observed that the outage of lines 10, 1, 3, 15 and 7 are the most critical contingencies. For these lines, various sensitivity indices are computed by placing TCSC with 20% compensation. The results are tabulated in Table 3. According to the sensitivity indices calculated, the line number 10 is the optimal one for placement of TCSC as it is having the highest sensitivity index.

Table 2. Active power performance index for all line outages

Line number	From bus-To bus	PIP	Rank
1	1-2	9.680	2
2	1-5	5.329	7
3	2-3	8.562	3
4	2-4	5.170	10
5	2-5	3.980	19
6	3-4	3.910	18
7	4-5	5.661	5
8	4-7	5.350	6
9	4-9	4.958	8
10	5-6	10.860	1
11	6-11	4.606	14
12	6-12	4.462	15
13	6-13	5.182	9
14	7-9	5.554	4
15	9-10	4.405	12
16	9-14	4.869	11
17	10-11	4.324	16
18	12-13	4.217	17
19	13-14	4.372	13

Table 3. Sensitivity indices by placing TCSC with 20% compensation

Line number	RPSI	RLSI	QLSI	Rank
10	**-0.0311**	**-0.0011**	**-0.0138**	**1**
1	-0.1013	-0.0042	-0.0542	2
3	-0.1027	-0.0042	-0.0551	3
15	-0.1133	-0.0047	-0.0612	4
7	-0.1168	-0.0049	-0.0634	5

4.4. Optimal loaction of SVC

The VBF is computed by placing the SVC of specified size at all the buses and results are tabulated in Table 4. As bus number 10 is having the highest VBF, it is considered as suitable location for placing SVC. Upon deciding the suitable location for placement of SVC, ATC results are obtained without SVC and with SVC at bus number 10, 14 and 9 and are tabulated in Table 5. It is observed from the table that ATC is enhanced on placing SVC at bus number 10 compared to bus number 14 and 9.

Table 4. Voltage benefit factor on placement of SVC at all buses

Load Bus number	VBF	Rank
4	-0.0320	5
5	-0.0700	6
7	-0.0890	7
9	0.2300	3
10	**0.2970**	**1**
11	0.1320	4
12	-0.1150	8
13	-0.210	9
14	0.2570	2

Table 5. ATC in MW after placing SVC and TCSC at optimal location

Source Bus	Sink Bus	ATC without SVC	ATC in MW after placing SVC at load bus 10	ATC in MW after placing TCSC on line number 10
2	5	16.4877	16.7536	17.260
2	6	10.6660	11.9735	12.8721
3	5	27.3312	27.7720	28.5987
3	6	10.9613	12.3051	12.5142

5. CONCLUSION

The calculation and improvement of available transfer capability helps to solve the problem of transmission network congestion which is arising due to deregulation in today's power industry. This paper presents a simple and computationally efficient method for evaluation of ATC for a given system and presents an approach for placing of appropriate size of TCSC and SVC at a suitable location in the system to enhance ATC. As the power system is moving from centralized generation to distributed generation these days, the advantage of having renewable sources to enhance ATC can be an extended work. Also, the approach proposed in the paper can be further used in developing intelligent system which estimates the ATC of given system during existing loading conditions very quickly so as to avoid the network congestion and make the whole power system more reliable.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

Ethical approval is not applicable as this paper as not talk about using people or animals.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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