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Hybridized Continuous-Repeated Power Flow (HCR-PF) for Electric Power Transfer Capability determination

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ABSTRACT

The ability to accurately and rapidly assess the capabilities of the transmission grid is a key concept in the restructuring of the electric power industry. This paper presents hybridized Continuation-Repeated Power Flow (HCR-PF) for ATC computation. Results of IEEE 9 bus and IEEE 30 bus test systems were presented and comparisons were made with other methods. HCR-PF is seen to provide a good alternative to determine ATC. Single line outage (N–1) criterion is used to simulate the effect of line outages on ATC values thereby identifying overloaded transmission facility. Network response method for results interpretation of ATC is considered appropriate since it takes into consideration the response of the entire network to a given transfer direction. Although any limitation may be considered independently for simulation purposes, in practice any of the limiting constraints can be the most severe, depending on system base case and steady state variables.

Keywords: *Available Power Transfer, Continuation Power Flow, Repeated Power Flow and contingency.*

1. INTRODUCTION

In power systems planning and operations, the ability to accurately and rapidly assess the capabilities of the transmission grid is a key concept in a deregulated electricity market (Sauer, 1997). Information about transfer capability between various interfaces of a power grid is vital for the bulk power market. Power system Engineers and Planners need to know the system bottlenecks (Generation-Transmission interface constraints, Transmission Substation capacity constraints, Transmission wheeling constraints, Transmission-Distribution interface constraints) and system operators must implement transfers within the calculated transfer capability. These bottlenecks if not properly managed result to Load Shedding, Voltage/Frequency instability, and Stranded power (Akinniranye, 2012). Repeated estimation of transfer capabilities are needed to ensure that the combined effects of power transfers resulting from multilateral transactions do not cause undue risk of system overloads, equipment damage, blackouts or system collapse.

Transfer capability of transmission interface can be specified as either Available Transfer Capability (ATC) or Total Transfer Capability (TTC). Transfer capability computations from one point to another (buses) are generally based on a snap shot of the system: system loading, generation dispatch, thermal overload, topology, voltage and/or stability limits as well as contingencies considered (Sadiq A, Nwohu M, et al 2013) (Mark and Chika, 1999; Dobson, et al., 2001).

Hence, there existed different approaches to transfer capability assessment, these are classified as deterministic or probabilistic depending on system parameters considered either fixed or varied during operating conditions. Transfer capability is also catalogued based on different time horizons, planning and operating (real time) capabilities. For real time (on-line) calculations, system generation and load demands are often regarded as fixed values and the entire power network is a snapshot of the highly dynamic system. This assumes a static feasible operating condition upon which an incremental transfer can be imposed on the base case power flow. Operating transfer capability analysis is for real time or immediate future and the aim is focused on contingency analysis. Single line outage (N-1 criterion) contingency is often considered. Transfer capability for planning analysis is in the long-term horizons, due to large number of uncertainties in system parameter variation. Here, the focus is on considering all likely base cases and contingencies. Hence long term ATC parameters take on probability distribution (Yuan-Kang, 2007).

Four major approaches are suggested in the literature for the calculation of ATC:

I. Sensitivity analysis

Sensitivity analysis employs Factors which include: line outage distribution factors (LODF), Power Transfer distribution factor (PTDF) and Generation sift factors (GSF). These can be based on DC or AC power flow. It does not take into account the non-linear effects of reactive power and voltages (Mark and Chika, 1999, Greene, S., 2002).

II. Optimal power flow (OPF)

Optimal power flow (OPF) method maximizes Transfer Capability between sources and sinks thereby respecting contractual terms and economic dispatch of generation. However, open access allows transaction in practice from/to any point/area (Shaaban, M., Ni, Y., & Wu, F. F. 2000).

III. Continuation power flow (CPFLOW)

Initially introduced to find maximum loadability, CPFLOW is applicable to ATC computation without change in principle. Involve complex parameterization or perpendicular intersection and able to define ATC for thermal, voltage and stability constraints. CPFLOW Implemented by a new Power system software package Power System Analysis Toolbox (PSAT) (Chih-wen, L., et al 2005).

IV. Repeated power flow (RPF)

Easy to implement but involves solving full AC power flow at each transfer step. Similar to CPFLOW it increases complex power demand at sink buses and power supply at sources at a given step until a binding security limit is just encountered. It however does not trace the full nose of the system under simulation (Ejebe, G., et al 1998).

Each of these methods can lend themselves to deterministic or probabilistic method. Equally important in transfer capability assessment is the interpretation of results; often two methods are used; Rated system path (RSP) method and Network response (NR) method. In network response method, transfer capability from bus (A) to another bus (B) is the maximum real power transferable from (A) to (B) by all physical paths connecting buses (A) to (B). While in the rated system path method, transfer capability from bus A to bus B is the real power (maximum) flow over the physical paths directly connecting buses (A) and (B) under a limiting condition which is system-wide (Sauer, 1997). Table 1 shows the performance comparison of various deterministic ATC methods based on the limitations to power transfer (Dobson, I., et al 2001).

1.1 Limitations to Electric Power Transfer

The ability of interconnected transmission network to transfer quality electrical power reliably and economically may be limited by physical, environmental and electrical characteristics of the systems (NERC, 1996). Transfer capability computations are mainly a function of three limits: Thermal limit overload, Voltage limits and Stability limits. (Marannino, *et al*., 2002). Figure depict Transfer Capability quantities, msrgins and limitations.

Figure1: Transfer Capability Margins and limitations.

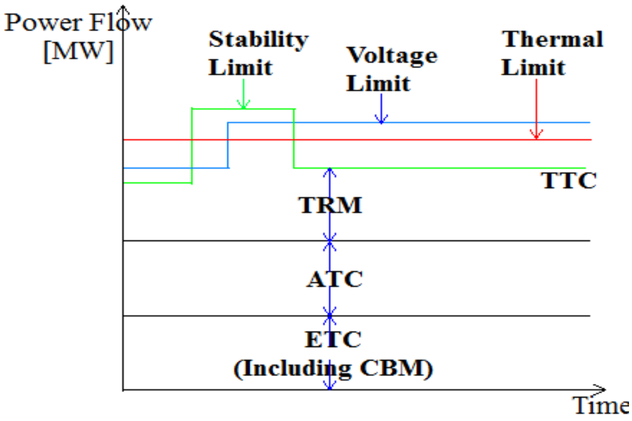

Table 1: Comparison of various Transfer Capability methods.

	Constraints Considered		
Method	Thermal	Voltage	Stability
DCPF	Yes	No	No
PTDF	Yes	No	No
LODF	Yes	No	No
GSF	Yes	No	No
RPF	Yes	Yes	Yes
CPFLOW	Yes	Yes	Yes
OPF	Yes	Yes	Yes

Source: (Hojabri and Hizam, 2011)

1.2 Generic Transfer Capability

Approaches to Transfer Capability computations differs, however, each method adopted should some basic framework as acknowledged by the regulatory agency this makes Transfer Capability peculiar a given Power utility. It is beneficial to consider a simple case of Transfer Capability computation with limited set of network parameter variations. A single Transfer Capability computation between the source-sink buses should yield:

1. A base case (feasible operating condition).
2. Transfer direction including the source, sink and losses (or a lossless Transfer).
3. A solved transfer-limited case which includes the Transfer capability at base case and the incremental transfer imposed that result to binding security limit.
4. The transfer margin is the difference between the power transfer at the base case and the power transfer resulting to the limiting case.

The base case and the transfer direction are inputs to the system while the transfer capability and the limiting constraints are the output.

2. METHODOLOGY

2.1 Reformulation of Power Flow Equation

To apply continuation method to power flow problem, a loading parameter must be inserted into the power flow equations to parameterize the load-flow equation (Venkataramana and Colin, 1992). A constant power load model is documented as follows:

Let the loading parameter (λ) be represented by equation (1)

$$0 \leq \lambda \leq \lambda_{\text{limited}} \qquad (1)$$

where λ = 0 corresponds to the base case loading and $\lambda = \lambda_{\text{limited}}$ corresponds to the maximum loading parameter above which a binding security limit is encountered. For an n bus system, the normal power flow equation of each bus i can be expressed in equations (2), (3), (4) and (5).

$$P_G^i - P_L^i - P_{\text{injected}}^i \qquad (2)$$

$$P_{\text{injected}}^i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j + \theta_{ij}) \qquad (3)$$

$$Q_G^i - Q_L^i - Q_{\text{injected}}^i = 0 \qquad (4)$$

$$Q_{\text{injected}}^i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j + \theta_{ij}) \qquad (5)$$

where G and L denotes generation and load; bus voltages at buses i and j are given by $V_i \angle \delta_i$ and $V_j \angle \delta_j$ while $Y_{ij} \angle \theta_{ij}$ is the (i, j)th element of the bus admittance matrix.

For Available Transfer Capability calculation, the injected power (Real and Reactive) both at source and sink buses are functions of lambda (λ). In order to simulate a load change, P^i, Q^i and P^i_G terms must be modified such that each term be made of two components: the base case component and the component due to change in loading parameter (Liang and Ali, 2006; Venkataramana and Colin, 1992). Thus,

$$P_L^i = P_L^{i0}(1 + \lambda K_{pi}) \quad (6)$$

$$Q_L^i = Q_L^{i0}(1 + \lambda K_{Qi}) \quad (7)$$

$$P_G^i = P_G^{i0}(1 + \lambda K_{Gi}) \quad (8)$$

where $P^i{}_G, P^i{}_L, Q^i{}_L$ are the real power generation, load and reactive load at i^th^ bus while $P^{i0}{}_G, P^{i0}{}_L, Q^{i0}{}_L$ are their corresponding base case schedules. K_{Pi}, K_{Qi} and K_{Gi} are participation factor to designate the variation of real and reactive power at PQ buses and real power variation at PV buses (sensitivity of load and generation changes at the i^th^ bus) as lambda (λ) changes.

When these new equations (6), (7) and (8) are inserted into (2) and (4) the resulting power flow equations become parameterized and given in (9), (10).

$$P_G^{i0}(1 + \lambda K_{Gi}) - P_L^{i0}(1 + \lambda K_{pi}) - P_{\mathrm{injected}}^i = 0 \quad (9)$$

$$Q_G^{i0} - Q_L^{i0}(1 + \lambda K_{Qi}) - Q_{\mathrm{injected}}^i = 0 \quad (10)$$

At generator (PV) buses, the term K_{Qi} is zero while at load (PQ) buses a constant power factor is maintained by making the ratio $\frac{K_{pi}}{K_{Qi}}$ constant.

For an inter-area transfer schedule, the nonlinear power flow equation parameterized with lambda (λ) can be expressed in compact form as in equations (11) and (12).

$$f(x, \lambda) = 0 \quad (11)$$

$$f(x, \lambda) \equiv f(x) - \lambda b \quad (12)$$

where the state variable $x = (\delta, V)$ is a vector of bus voltage magnitude and angles.

The formulation by Mark and Chika, (1999), and Wu and Fischl, (1993), show that there is a close connection between optimization, CPFLOW and repeated power flow (RPF) or successive iterative load flow computation for Transfer Capability computations. CPFLOW can therefore solve the power flow equation as an optimization problem stated thus (Prabha, *et al.*, 2010):

$$\max(\lambda)$$

Subject to

$$f(x, \lambda) = 0 \quad (13)$$

$$|P_G^i|_{\min} \le |P_G^i| \le |P_G^i|_{\max} \quad (14)$$

$$|Q_G^i|_{\min} \le |P_G^i| \le |Q_G^i|_{\max} \quad (15)$$

$$|V_i|_{\min} \le |V_i| \le |V_i|_{\max} \quad (16)$$

$$|P_{ij}|_{\min} \le |P_{ij}| \le |P_{ij}|_{\max} \quad (17)$$

Equations (13) is the compact power flow equation, (14) and (15) are the PV real and reactive power limitations, (16) is the bus voltage limits while (17) is the thermal limits of lines connecting buses. At the maximum loading parameter (λ_{max}), the ATC is calculated using equation (18) (Chanrasekar and Ramana, 2011; Yan and Chanan, 2002).

$$ATC = \sum_{i \in sink} P_L^i(\lambda_{\max}) - \sum_{i \in sink} P_L^{i0} \quad (18)$$

2.2 Hybridized Continuous-Repeated Power Flow (HCR-PF)

The proposed approach to determine ATC is the hybridized Continuous-Repeated (HCR) structure. The continuation power flow (CPFLOW) and repeated power flow (RPF) are both ac power flow methods which give accurate solution in determining the ATC because it considers the effect of reactive power flow and voltage magnitude limit (Othman, 2006). The CPFLOW algorithm effectively increases the controlling parameter in discrete steps and solves the resulting power flow problem at each step. The procedure is continued until a given condition or physical limit preventing further increase is reached. Newton power flow algorithm is used. CPFLOW yields solutions even at voltage collapse points. The ac load flow power system models such as continuation power flow (CPFLOW) can handle the three power flow limits, namely, thermal, voltage magnitude, and stability constraints (Ejebe, *et al* 1998).

Both CPFLOW and RPF implement transfers by increasing complex load with uniform power factor at every load bus in sink area with corresponding increase in the real power injection at generator buses up to a binding security limit. The proposed algorithm is implemented in Power System Analysis Toolbox (PSAT) and summarized below:

I. Establish a feasible base case, by specifying generation and loading level, bus voltage magnitude and limits as well as line/transformer thermal limits.
II. Run the resulting feasible base case power flow using Newton Raphson (NR) power flow.
III. Specify transfer direction by connecting power supply bid block at all generator buses in source area and connecting power demand bid block at all load buses in sink area
IV. Set up and run CPFLOW in PSAT with specified number of points and step size control.
V. Check for limit violation in IV
VI. If yes, reduced step size else increase step size until the binding security limit is just removed or about to be encountered.
VII. Calculate ATC using equation (3.15) and report ATC value and the binding limitation.

Figure 2 shows the flow chart of the proposed Hybridized Continuous-Repeated Power Flow structure.

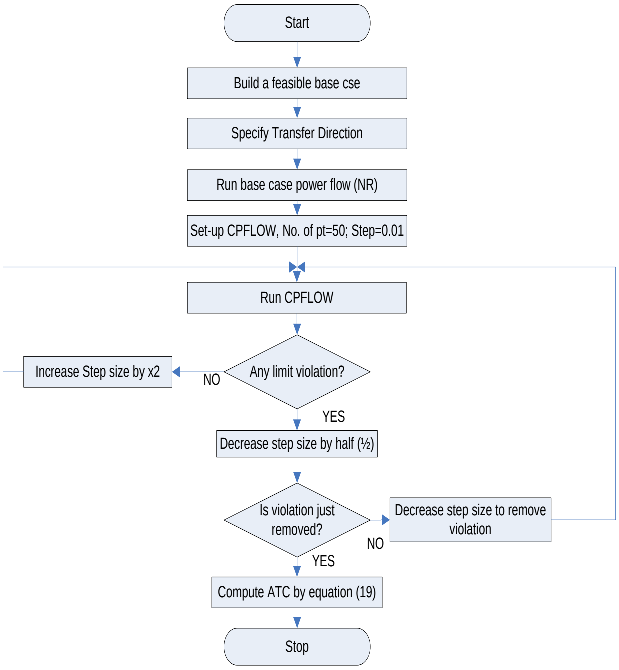

Figure 2: Flowchart of the proposed Hybridized Continuous- Repeated Power Flow Structure.

2.3 Step-size Control of HCR-PF

As shown in Figure 3.6, the step size implementation proposed in the hybridized CPFLOW – RPF structure start with a step – size of 0.01 corresponding to a loading point A. If there is no violation (Line thermal limits, voltage magnitude and generator reactive power), CPFLOW – RPF structure increase the step size to a loading point B (0.02) and then to loading point C (0.04) where a limit violation is encountered. CPFLOW – RPF structure then reduces the step size by half of the increment between point B (0.02) and C (0.04) to a new loading point D (0.03); should there be violation at this new point, the structure move to point E (0.025) and continues in that process.

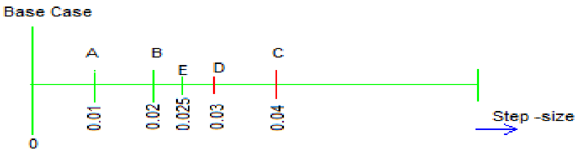

Figure 3: Step-size control implementation of the Hybridized Continuous-Repeated Power Flow Structure.

3. RESULTS AND DISCUSSIONS

3.1 IEEE 9 Bus Test System

The proposed method was implemented on IEEE 9 bus test system. Table 2 gives the results and a comparison is made with Adaptive Neuro-Fuzzy Inference System (ANFIS) method. Figure 4 gives the PSAT model of the IEEE 9 bus test system.

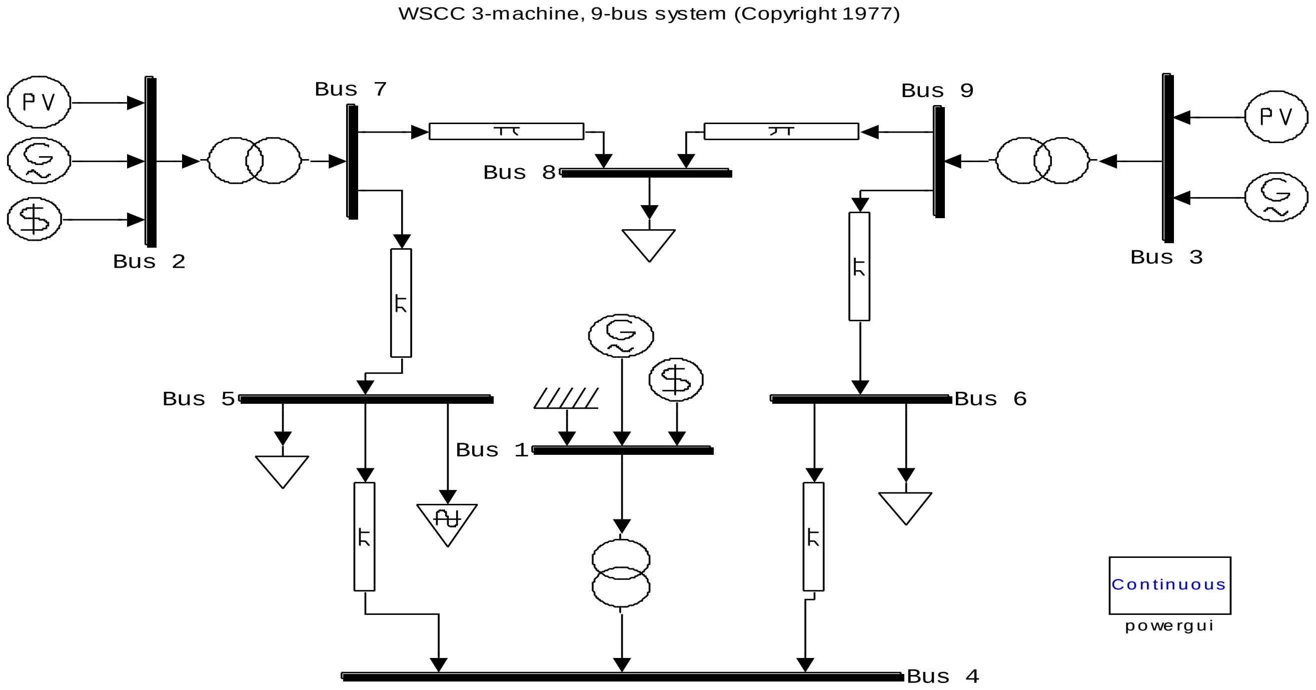

Figure 4: PSAT model of IEEE 9 bus test System.

Table 2: Comparison between HCR-PF and ANFIS method for thermal and voltage limitation various Transactions of IEEE 9 bus test system

TRANSACTION/METHOD	ATC_{TL}(MW) HCR-PF	ATC_{TL} (MW) HCR-PF (Pij)	ATC_{TL}(MW) ANFIS	ATC_{VL} (MW) HCR-PF	ATC_{VL} (MW) HCR-PF (Pij)	ATC_{VL} (MW) ANFIS
T1	66.39	68.11	65.36	146.50	152.37	156.77
T2	67.44	72.99	84.07	106.27	81.56	89.99
T3	88.24	92.70	NO VIOLATION	117.18	123.85	84.22
T4	66.79	71.82	117.05	107.65	117.28	133.78
T5	66.49	73.35	NO VIOLATION	91.16	102.08	79.34
T6	88.45	92.92	73.24	116.53	123.15	154.89
T7	66.83	73.75	144.6	92.95	103.88	127.13

From Table 2, observe that the interpretation of ATC results by either Rated system path (RSP) method or Network response (NR) method using HCR-PF gives different ATC values while ANFIS method gives a too optimistic ATC values. Transactions T3 and T5 shows no violation due to thermal limitation by the ANFIS method, this is rare if not impossible; each transmission line has a rated current carrying capacity which translate to it thermal constraints.

Figure 5 depict comparison between ATC_{TL}(MW) constrained by thermal limitation using HCR-PF and ANFIS. The ATC_{TL}(MW) HCR-PF (Pij) gives the interpretation of ATC results by Rated system path (RSP) while ANFIS method implemented only Rated system path (RSP). From Figure 5, Transactions T3 and T5 by implication mean an infinite ATC.

Figure 5: Comparison between ATC_{TL}(MW) constrained by thermal limitation using HCR-PF and ANFIS.

Figure 6 depicts Comparison between ATC_{VL} (MW) constrained by Voltage limitation using HCR-PF and ANFIS. Again ANFIS provides too optimistic results for ATC computation.

In addition, the last corrector step solution result of HCR-PF in PSAT environment which is obtainable in Excels identifies the limitation type and element rather than the searching techniques.

IEEE 30 Bus Test Systems

Table 3 gives the contingency ATC values of IEEE-30 bus system, which shows the comparison between the HCR-PF and that presented in reference (Yuan-Kang, 2007). Various transactions were implemented for both contingency and normal study cases for IEEE-30 bus system and the results obtained were compared.

Figure 6 depicts the comparison of Table 3. HCR-PF is seen to provide a good alternative to ATC computation. Observe that from Table 3, the limiting lines to the contingency ATC values are same for both method compared.

To further validate the proposed method, ATC expected values among different network buses of the IEEE-30 bus system were also computed as shown in Table 4.

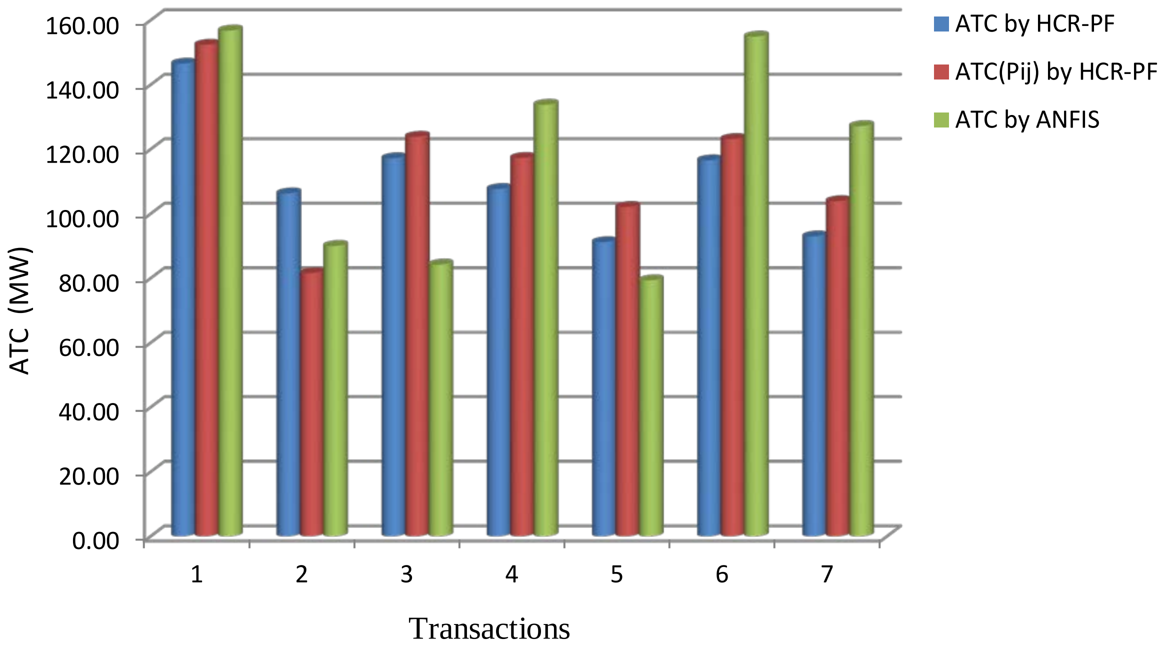

Figure 6: Comparison between ATC_{VL} (MW) constrained by Voltage limitation using HCR-PF and ANFIS.

Table 3: Contingency ATC Values from Bus 14 to Bus 21 of IEEE-30 bus

Bilateral Transaction	Outage Line		Limiting Line		ATC By Hybridized C-RPF	ATC By WU's Method
	From	To	From	To	ATC (MW)	ATC(MW)
From Bus 14 To Bus 21	12	14	14	15	22.2	22.2
	12	15	14	15	13.4131	13.5376
	12	16	14	15	28.77	28.0768
	14	15	10	21	28.49	28.4403
	15	18	10	21	33.7824	33.7682
	15	23	10	21	21.227	21.7515
	16	17	14	15	28.3627	28.8257
	10	17	10	21	29.3251	29.4786
	18	19	10	21	33.4643	32.5241
	19	20	10	21	28.7402	28.7572
	10	20	10	21	27.5504	27.9273
	10	21	21	22	11.669	14.289
	10	22	10	21	12.0471	13.1917
	22	24	10	21	27.8676	27.8809
	23	24	10	21	24.0214	24.1305

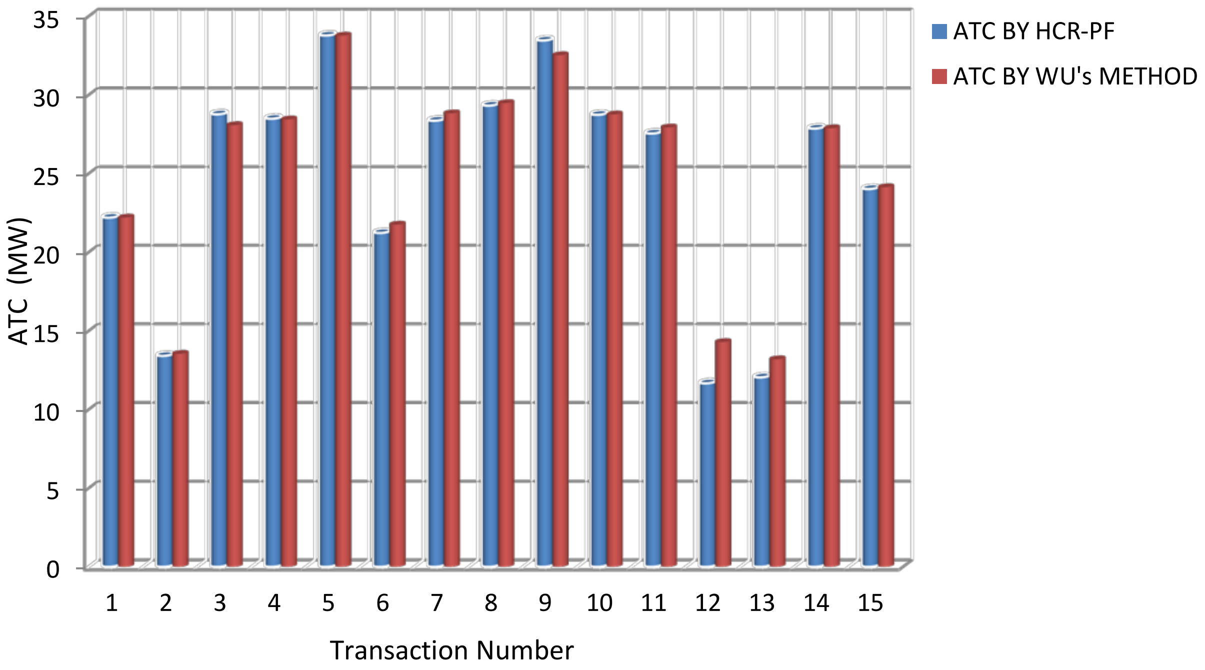

Figure 6: Comparison between ATC using HCR-PF and WU’s Method.

4. CONCLUSION

This paper shows that Hybridized Continuous-Repeated power flow (HCR-PF) provides a good approximate alternative for Available transfer capability evaluation. Normal and contingency ATC(s) were computed. Single line (N – 1) outage criterion was used as contingency. It implemented both Rated system path (RSP) method and Network response (NR) method using HCR-PF for ATC results interpretation. Various transactions of IEEE 9 bus and IEEE 30 bus test systems using HCR-PF were implemented.

Table 4: A Comparison between ATC Methods in IEEE-30 bus systems

Comparison on ATC expected values among different network buses in the IEEE-30 bus system												
	ATC Expected values from bus 14 to other buses (MW)											
	From Bus	14	14	14	14	14	14	14	14	14	14	14
1	To Bus	15	16	17	18	19	20	21	23	24	26	29
	ATC (MW) Wu method	25.6	33.9	31.9	15.6	19.9	23.4	28.2	16.7	22.8	12.3	13.6
	ATC (MW) HCR-PF	25.4	32.9	30.8	15.0	16.8	23.0	28.0	13.0	11.0	10.3	13.0
	ATC Expected values from bus 15 to other buses (MW)											
	From Bus	15	15	15	15	15	15	15	15	15	15	15
2	To Bus	14	16	17	18	19	20	21	23	24	26	29
	ATC (MW) Wu method	29.7	41.1	38.2	14.7	18.5	21.5	31.3	15.8	24.3	12.3	13.6
	ATC (MW) HCR-PF	30.6	37.6	32.1	14.3	17.4	20.9	29.3	11.4	12.3	10.4	13.2
	ATC Expected values from bus 16 to other buses (MW)											
	From Bus	16	16	16	16	16	16	16	16	16	16	16
3	To Bus	14	15	17	18	19	20	21	23	24	26	29
	ATC (MW) Wu method	38.9	28.9	19.4	18.8	25.4	26.7	23.0	19.5	18.7	12.3	13.6
	ATC (MW) HCR-PF	37.8	24.2	17.4	18.0	14.6	25.3	22.1	14.1	9.5	11.0	12.6
	ATC Expected values from bus 17 to other buses (MW)											
	From Bus	17	17	17	17	17	17	17	17	17	17	17
4	To Bus	14	15	16	18	19	20	21	23	24	26	29
	ATC (MW) Wu method	36.8	35.7	24.6	21.5	30.7	30.3	25.6	21.6	16.6	12.3	13.6
	ATC (MW) HCR-PF	37.4	28.1	25.2	20.4	27.5	28.5	24.7	14.8	8.9	10.7	12.6
	ATC Expected values from bus 18 to other buses (MW)											
	From Bus	18	18	18	18	18	18	18	18	18	18	18
5	To Bus	14	15	16	17	19	20	21	23	24	26	29
	ATC (MW) Wu method	29.6	28.0	33.4	28.8	16.7	18.7	26.1	17.7	20.3	12.3	13.6
	ATC (MW) HCR-PF	30.3	28.3	33.1	28.3	16.1	18.1	26.3	13.0	11.2	10.7	12.5
	ATC Expected values from bus 19 to other buses (MW)											
	From Bus	19	19	19	19	19	19	19	19	19	19	19
6	To Bus	14	15	16	17	18	20	21	23	24	26	29
	ATC (MW) Wu method	32.4	30.1	35.7	32.3	21.0	42.9	27.3	19.0	18.7	12.3	13.6
	ATC (MW) HCR-PF	32.5	30.0	35.6	32.9	21.2	42.1	26.3	13.4	10.0	10.6	12.6
	ATC Expected values from bus 20 to other buses (MW)											
	From Bus	20	20	20	20	20	20	20	20	20	20	20
7	To Bus	14	15	16	17	18	19	21	23	24	26	29
	ATC (MW) Wu method	33.6	34.9	33.8	31.2	23.2	26.8	26.7	19.8	17.9	12.3	13.6
	ATC (MW) HCR-PF	33.7	34.4	34.5	32.0	23.1	25.0	25.8	14.0	10.0	10.5	12.2
	ATC Expected values from bus 21 to other buses (MW)											
	From Bus	21	21	21	21	21	21	21	21	21	21	21
8	To Bus	14	15	16	17	18	19	20	23	24	26	29
	ATC (MW) Wu method	34.8	35.3	30.1	28.9	22.2	32.1	29.7	21.9	14.5	12.3	13.6
	ATC (MW) HCR-PF	31.5	27.2	30.7	29.3	21.6	29.3	28.4	13.2	6.9	10.5	12.4
	ATC Expected values from bus 23 to other buses (MW)											
	From Bus	23	23	23	23	23	23	23	23	23	23	23
9	To Bus	14	15	16	17	18	19	20	21	24	26	29
	ATC (MW) Wu method	27.1	25.7	31.6	33.8	16.4	21.2	25.2	29.9	22.5	12.3	13.6
	ATC (MW) HCR-PF	26.4	26.1	30.4	31.9	15.8	19.6	24.0	27.6	15.3	10.7	12.3
	ATC Expected values from bus 24 to other buses (MW)											
	From Bus	24	24	24	24	24	24	24	24	24	24	24
10	To Bus	14	15	16	17	18	19	20	21	23	26	29
	ATC (MW) Wu method	33.9	36.3	34.6	31.3	19.3	26.3	32.3	30.2	24.5	12.3	13.6
	ATC (MW) HCR-PF	34.8	36.9	34.8	31.9	18.5	23.6	30.3	30.2	24.2	10.4	12.5

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