

A COMPUTER CALCULATION FOR TENTATIVE ELECTRICAL SYSTEM IMPROVEMENT BY REACTIVE POWER COMPENSATION CONSIDERING SYSTEM UNBALANCED

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Abstract—An improvement of unbalanced distribution system operation is carried out by reactive power compensation. The lagging reactive power demand is compensated by allocating a number of three-phase shunt capacitors. At the stage, the compensation devices are determined tentatively in term of number, size and location. The effects of the installed shunt capacitors are then analyzed. The unbalanced condition of distribution system is taken into account due to the fact that distribution system is inherently imbalance. For three-phase unbalanced power flow analyses, forward-backward propagation algorithm is proposed. The algorithm works directly on the system without any modification. Starting with determination of forward and backward propagation paths, the algorithm calculates branch currents using backward path. With the branch currents in hand, the bus voltages are calculated using the obtained branch currents and line impedances. Equivalent injection currents representing loads and shunt admittances method are required. The algorithm offers robust and good convergence characteristics for radial distribution system. In this paper, reactive power compensation is simulated using tentative approach and the achieved system improvements are observed. The improvements are presented as losses minimization and voltage profile enhancement. The simulation is carried out for the IEEE 34-bus system, while the system improvements due system compensation are described. The generated results indicate that for further optimal system improvement, an optimization technique is required.

Keywords; *Forward-Backward Propagation Algorithm, power loss, reactive power compensation, unbalanced system, voltage profile*

I. INTRODUCTION

The objective of electrical distribution system operation is to satisfy the customer electricity demand in both technically acceptable and economically optimal. Since the nature of the demand keeps changing in term of quantity, the aforementioned objective may not be easily achieved. In addition to complexity of satisfying the changing load, if not carefully managed, load variations may result in electricity demand not being fully satisfied, unacceptable quality of the

electricity supplied to the customer, voltage violation and extensive power losses.

The limitation of power plant firing capacity generally occurring in Indonesia necessitates that every watt-generated power should be transmitted and utilized optimally. It is therefore required that the transmission and distribution losses should be maintained as minimum as possible. The insufficient power generation as well as the high lagging reactive power may lead the system to violate the permitted voltage limits resulting in low power quality supplied to the customer. Establishing new power plants will be a solution to satisfy load demand and to maintain the acceptable voltage profile. However, the expensive investment of building the new power plant followed by the high operation cost -for that energized by fossil fuel- will be the main issues for the government or utility company to consider.

An adaptable enhancement may therefore be required to improve system operating performance by minimizing the network losses and, at the same time, improving the system voltage profile. The distribution system is part of electrical system that contributes dominant losses on the system. Distribution system is the part of electrical system closest to the customer and load center that may suffer from voltage violation and losses escalation because of load variation. Therefore, optimal control of distribution system operation may result in significant system improvements.

One of the control strategies is reactive power compensation that may simultaneously improve the voltage profile and minimize the losses. This may be carried out by properly installing shunt capacitors in the distribution network to compensate the lagging power factor loads. The compensation may lead to voltage improvement and losses minimization. However the shunt compensation devices need to be carefully placed in the system to achieve the compensation advantages and to avoid any possible negative impact. Computer simulation is somehow necessary to assure a successful real implementation.

Distribution system is inherently unbalanced, due to the facts of unbalanced customer loads, the presence of unsymmetrical line spacing, and the combination of single, double and three-phase line sections. As a result, analyses for

reactive power compensation should take the unbalanced conditions into account. The most important calculation for reactive power compensation is power flow analysis used as the backbone of compensation calculation. Consideration of system unbalanced requires the power flow analysis to be carried out for all of the three phases.

Optimal reactive power/voltage control is a well-researched topic. The problem has been solved employing some methods resulting in satisfied results [1-4]. However, the optimization is so far carried out by assuming that both loads and systems are balanced. As a result, the calculations are performed for single phase assuming that the other two phases are exactly the same except the 120° phase different. Three-phase model of distribution system is required to represent the system more accurately.

Inclusion of unbalance increases the dimension of problem as all the three phases need to be considered instead of single phase balanced representation. On the other hand, distribution system commonly constructed as radial system may cause the sophisticated power flow algorithms fail to converge. The robust algorithm for three-phase power flow is therefore needed. In this paper, the method of Forward-Backward propagation algorithm is proposed for three-phase power flow analysis. The algorithm works directly on the system without any modification. Therefore, there is no need to decompose the system into symmetrical components as well as to decouple the system into individual phases. However, the conversion of load and shunt element into their equivalent injection current is necessary. Distribution line charging is usually too small to be included [5]. Assignment of the method is due mainly to robust characteristic of the method and high probability to converge. These two reasons are the most considered factors in appointing any power calculation method.

The reactive power compensation is simulated using tentative approach where shunt capacitors are installed in the system and the system improvements are observed. The simulation is carried out for the IEEE 34-bus system, asymmetrical lines and unbalance loads. The robustness of three-phase power flow is analyzed. For the effect of tentative reactive power compensation, the system enhancements due to the shunt capacitors installation are also described.

II. THREE-PHASE POWER FLOW

In order to simplify the problem, some approaches have been carried out for three-phase power flow problem. Decomposition of the coupled unbalanced system into positive, negative and zero symmetrical components is the most popular approach used for the problem [6, 7]. This eliminates the mutual coupling between phases such that a three-phase power flow calculation may be carried out by running single-phase power flow calculation for three times, once for each phase. However, for the coupling occurring between sequences, no real advantage of system decomposition that may be achieved. In addition, this may result in significant error in calculation.

Another approach for solving unbalanced power flow is decoupling three-phase system into individual phase by

introducing compensation current injections [5, 8-10]. Therefore, a three-phase power flow can be solved independently for every phase without utilization of symmetrical components. All components are modeled by phase voltages, admittances and independent current sources. This approach will work well as long as every component can be modeled in the admittance matrix or can be converted into equivalent injection current.

The methods for three-phase distribution networks can be basically divided into two classes, Gauss-Seidel [8, 11] and Newton-Raphson [5, 12, 13]. Gauss-Seidel method needs much iteration and is known to be slow. Newton-Raphson has good convergence characteristic, but the Jacobian that needs to be partially or totally calculated in every iteration makes this approach unattractive.

Distribution system is commonly constructed as radial system or sometimes weakly meshed system with high R/X ratio. These characteristics are the well-known obstacles that may cause the sophisticated power flow algorithms fail to converge. When R/X ratio increases, power flow iteration becomes unstable and may even diverge. Power flow analysis for unbalanced systems is therefore complicated requiring a robust power flow algorithm.

This paper uses forward-backward propagation algorithm for unbalance power flow analyses [14]. The algorithm works directly on the system without any modification. Conversion of load and shunt elements into their equivalent injection currents is required to form equivalent bus injection currents. Distribution line charging may be ignored in distribution system due to its small value [5]. The algorithm offers robust and good convergence characteristics for radial distribution system [14].

The accuracy of three-phase power flow results greatly depends on the system components model and, therefore, the proper model of line section, load and shunt admittance need to be firstly established. The model of distribution line feeder in [15] is developed and used in this paper. The three-phase load and shunt capacitors are represented by their equivalent injection currents using the model developed in [8].

With the components model in hand, the algorithm starts with mapping the distribution network to determine the forward and backward propagation paths. The backward and forward propagations are used to calculate branch current and bus voltage respectively.

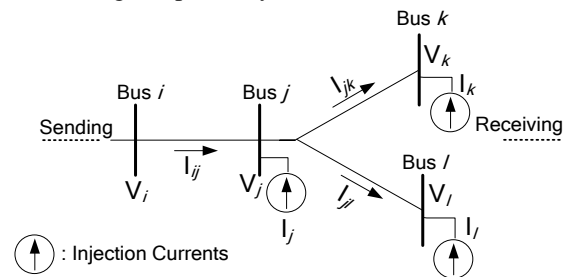


Figure 1. Fig.1. Part of a distribution system

The calculations may be explained in Fig. 1 and eqs. (1) and (2). From Fig. 1, the relationships between branch currents and injection currents are:

$$\begin{aligned}
 I_{jk} &= -I_k \\
 I_{jl} &= -I_l \\
 I_{ij} &= I_{jk} + I_{jl} - I_j
 \end{aligned} \tag{1}$$

where I_{jk} is the current flowing through the line section from bus j to bus k , and I_j is injection current at bus j . Following forward propagation path, bus voltages may be obtained by:

$$\begin{aligned}
 V_j &= V_i - Z_{ij}I_{ij} \\
 V_k &= V_j - Z_{jk}I_{jk} \\
 V_l &= V_j - Z_{jl}I_{jl}
 \end{aligned} \tag{2}$$

where V_j is the voltage at bus j and Z_{jk} is the impedance of line section between bus j and k . The bus voltages are then updated and bus injection currents are again calculated. The outlined calculations are repeated and the calculation converges if the different of bus voltages for the consecutive iterations is no more than the prescribed tolerance. Power loss calculations taking the difference between power in and power out per phase is used instead of using I^2R that may result in errors [15]. All calculations are carried in the three-phase frame.

The flowchart of unbalance power flow using Forward-Backward Propagation is given in Fig. 2.

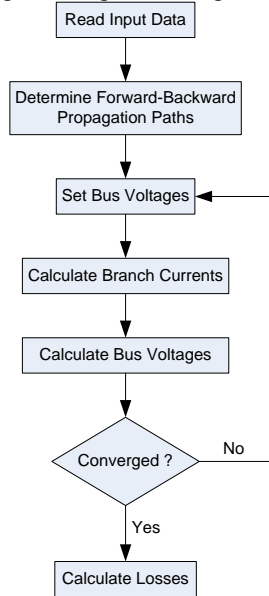


Figure 2. Three-phase power flow calculation using Forward-Backward Propagation Algorithm

III. SIMULATION

The IEEE 34-bus system including balance and unbalance loads [16] shown in Fig. 3 is used for simulation. A minor modification is carried out to only include three phase asymmetrical lines. The load data and the capacitor data are remain the same. The system data and conductors spacing are given in Appendix for convenience.

Three-phase power flow calculation for the system of Fig. 3 takes 5 iterations to converge. This iteration number is fairly small indicating that the algorithm is robust for

unbalance power flow calculation. The results of simulation including magnitude and angle of voltage at every phase are given in Table 1. The simulation also indicates the real and reactive power losses of 8.18 kW and 3.42 kVAR, respectively.

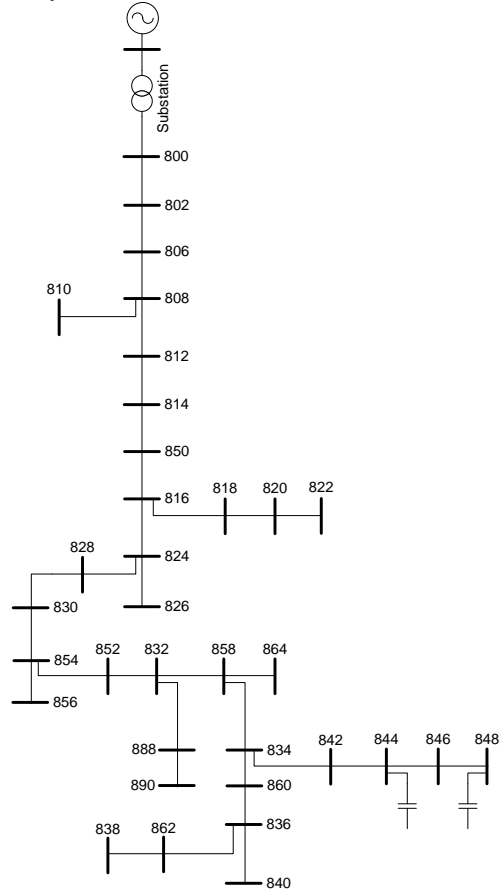


Figure 3. The IEEE 34-bus system used for simulation

IV. TENTATIVE REACTIVE POWER COMPENSATION

Case 1: Uncompensated System

In order to investigate the influence of installing shunt capacitors on distribution, a number of shunt capacitors are allocated on the simulated system. However, at this stage, no optimization method is employed and the number, size and location of the devices are determined tentatively. The analyses are carried out in terms of losses minimization and voltage profile improvement. It should be noted that the compensation result may not be the best one and it may be enhanced using optimization technique.

For the first case, the system is uncompensated, i.e. no compensation device is installed. This means that the system is operated without reactive power compensation and the bus voltage is not regulated. The minimum voltage for every phase is indicated below:

1. For phase A: 94,81% at bus 838
2. For phase B: 94,81% at bus 848
3. For phase C: 94,64% at bus 840

The result indicates that the minimum voltage at every phase lower than the minimum limit of 95% takes place in some buses. The complete results including bus voltage for every phase are not presented due to the limited paper space. The minimum voltage is figured to investigate if there is voltage lower than that minimum allowed limit. It may also be seen that the bus where the minimum voltage taking place is different. The losses for the system are 8.34kW and 6.02 kVAR for real and reactive losses, respectively.

TABLE I. UNBALANCE POWER FLOW CALCULATION RESULTS FOR THE SYSTEM OF FIG. 3

Bus no	Volt at phase c		Volt at phase c		Volt at phase c	
	Mag	Angle	Mag	Angle	Mag	Angle
800	100	0.00	100	-120.00	100	120.00
802	99.93	-0.01	99.94	-120.01	99.94	119.99
806	99.88	-0.02	99.89	-120.02	99.90	119.98
808	99.01	-0.22	99.19	-120.17	99.17	119.80
810	99.01	-0.22	99.18	-120.18	99.17	119.80
812	97.99	-0.45	98.38	-120.35	98.35	119.58
814	97.18	-0.64	97.75	-120.49	97.70	119.41
816	97.17	-0.64	97.74	-120.49	97.69	119.41
818	97.14	-0.64	97.74	-120.49	97.69	119.41
820	96.32	-0.66	97.84	-120.49	97.66	119.49
822	96.11	-0.67	97.88	-120.49	97.65	119.52
824	97.02	-0.69	97.50	-120.54	97.47	119.33
826	97.02	-0.69	97.49	-120.54	97.48	119.33
828	97.01	-0.69	97.48	-120.54	97.46	119.32
830	96.72	-0.81	97.08	-120.63	97.01	119.17
832	96.20	-1.02	96.36	-120.79	96.19	118.88
834	96.07	-1.08	96.17	-120.84	95.97	118.80
836	96.05	-1.08	96.15	-120.84	95.94	118.80
838	96.04	-1.08	96.14	-120.84	95.94	118.80
840	96.05	-1.08	96.15	-120.84	95.94	118.80
842	96.07	-1.08	96.17	-120.85	95.97	118.80
844	96.07	-1.09	96.16	-120.86	95.96	118.79
846	96.08	-1.11	96.15	-120.87	95.97	118.77
848	96.08	-1.11	96.16	-120.87	95.97	118.77
850	97.18	-0.64	97.75	-120.49	97.70	119.41
852	96.20	-1.02	96.36	-120.79	96.19	118.89
854	96.71	-0.81	97.07	-120.63	97.00	119.16
856	96.71	-0.81	97.06	-120.63	97.00	119.16
858	96.14	-1.05	96.27	-120.82	96.09	118.85
860	96.06	-1.08	96.16	-120.84	95.95	118.80
862	96.05	-1.08	96.15	-120.84	95.94	118.80
864	96.14	-1.05	96.27	-120.82	96.09	118.85
888	96.20	-1.02	96.36	-120.79	96.19	118.89
890	96.18	-1.02	96.34	-120.79	96.17	118.89

Case 2: Compensated System, 2 Shunt Capacitors

The system is now compensated using 2 shunt capacitors installed at bus 844 and bus 848. The detail of the compensation devices is indicated in Table 2. The appointment of the compensated buses is determined tentatively. However, one of the bus is that with low voltage.

For the system, the result of minimum voltage is

1. For phase A: 96.04% at bus 838

2. For phase B: 96,14% at bus 838
3. For phase C: 95,94% at bus 840

It may now be shown that the bus voltages have satisfied the minimum limit of 95%. The system losses are 8.18 kW and 3.42 kVAR, for real and reactive losses respectively. It may be seen that the system voltage has now improved and the losses are reduced. These improvements indicate the effective reactive power compensation for the system in hand. It should be noted the compensation results may be further improved if the compensation devices are optimally allocated.

TABLE II. TAB. 2 CAPACITOR COMPENSATION FOR THE 2ND CASE

No	Bus	Capacitance (kVAr)	Connection
1	844	100	Y – ungrounded
2	848	150	Y – grounded

Case 3: Compensated System, 3 Shunt Capacitors

An additional case is presented here with another shunt capacitor installed at bus 840. Bus 840 is selected since the bus is one of the bus with low voltage. A complete shunt capacitors for the system is indicated at Table 3.

TABLE III. CAPACITOR COMPENSATION FOR THE 3RD CASE

No	Bus	Capacitance (kVAr)	Connection
1	844	100	Y – ungrounded
2	848	150	Y – grounded
3	840	100	Y – ungrounded

For the optimized system, the minimum voltage is:

1. For phase A: 96.38% at bus 822
2. For phase B: 96.65% at bus 846
3. For phase C: 96.45% at bus 860

It may be seen that the voltage for the system with 3 compensation devices is even better, compared with that for the system with 2 shunt capacitors. Addition of a capacitor enables the system to further enhance the voltage profile. However, the location of minimum voltage takes place to the different buses. For system losses, the respective real and reactive losses are respectively 8.10 kW and 3.79 kVAR. While the real loss decreases, the reactive loss even increases with the addition reactive compensation devices. This indicates that tentatively allocate shunt capacitors may lead the system not to be as good as expected. Some sort of optimization method need to be employed of best compensation for the system.

Case 4: Compensated System, 4 Shunt Capacitors

The system is now compensated using 4 shunt capacitor with addition of a capacitor at bus 822. The appointment of bus 822 is because the minimum voltage for phase C takes place at the bus. The data for the installed shunt capacitors is indicated in Table 4. The minimum voltage for every bus for the system is:

1. For phase A: 96.91% at bus 838
2. For phase B: 97.06% at bus 846
3. For phase C: 96.86% at bus 860

TABLE IV. CAPACITOR COMPENSATION FOR THE 4TH CASE

No	Bus	Capacitance (kVAr)	Connection
1	844	100	Y – ungrounded
2	848	150	Y – grounded
3	840	100	Y – ungrounded
4	822	150	Y – grounded

It again confirms that the voltage has improved even better than that of system with 3 compensation devices. However, for losses minimization, the reactive power losses increases though the real loss has decreased. The losses for real and reactive losses are 7.87 kW and 4.33 kVAr, respectively. The results verify that, while the voltage and real loss have successfully been improved, the reactive loss even increases. It again highlights that an optimal shunt capacitors allocation needs to be determined using a kind of optimization technique.

V. CONCLUSION

Three-phase power flow is calculated using Forward-Backward Propagation algorithm for unbalanced distribution system. System enhancement by tentatively installing reactive compensation devices have also been carried out. The IEEE 34-bus unbalance system is used for simulation. The main conclusions are:

- The power flow algorithm works directly on the system and, therefore, there is no requirement of transforming the system into the symmetrical components as well as to decouple the three-phase into individual phases;
- The algorithm is known to be robust for radial unbalance system with good convergence characteristic;
- The reactive power compensation for distribution system may enhance system operating condition including voltage profile improvement and system losses minimization,
- Optimally allocate shunt capacitors on distribution system will further improve system operating condition without deteriorating the system.

VI. ACKNOWLEDGEMENT

The Authors would like to acknowledge that this research is funded by Ditlitabmas DIKTI under the scheme of Penprinas MP3EI year 202/2013.

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VIII. APPENDIX

TABLE A. BALANCE LOADS OF IEEE 34-BUS SYSTEM

Bus #	Y/Δ	Phase A		Phase B		Phase C	
		kW	kVAr	kW	kVAr	kW	kVAr
860	Y	19.91	15.94	19.91	15.94	19.91	15.94
840	Y	8.86	7.09	8.86	7.09	8.86	7.09
844	Δ	133.44	106.83	133.44	106.88	133.44	106.88
848	Y	19.45	15.57	19.45	15.57	19.45	15.57
890	Δ	27	21.62	27	21.62	27	21.62

TABLE B. UNBALANCE LOADS OF IEEE 34-BUS SYSTEM

Bus #	Y/Δ	Phase A		Phase B		Phase C	
		kW	kVAr	kW	kVAr	kW	kVAr
806	Y	0	0	31.22	16.14	26.07	13.84
810	Δ	0	0	15.88	8.21	0	0
820	Δ	33.9	17.52	0	0	0	0
822	Y	135.53	70.07	0	0	0	0
824	Y	0	0	0.39	0.2	0	0

826	Y	0	0	41.93	21.68	0	0
828	Δ	0	0	0	0	2.78	1.44
830	Δ	6.18	3.2	0	0	0	0
834	Y	3.99	2.06	12.55	6.49	12.82	6.63
836	Δ	27.37	14.15	10.55	5.45	42.05	21.74
838	Δ	27.61	14.27	0	0	0	0
840	Y	17.49	9.04	21.81	11.27	0	0
842	Y	0	0	0	0	0	0
844	Δ	9.12	4.71	0	0	0	0
846	Y	0	0	24.59	12.71	22.23	11.49
848	Y	0	0	22.62	11.7	0	0
856	Y	0	0	3.71	1.92	0	0
858	Δ	6.68	3.45	1.08	0.56	5.35	2.77
860	Y	15.66	8.09	20.86	10.78	111.15	57.46
862	Y	0	0	0	0	0	0
864	Δ	0.63	0.33	0	0	0	0

Swing : bus 800; MVA base: 2.5 MVA

Fig. A shows the spacing distances between the phase conductors and the neutral conductor. The line configuration is given in Table C (3rd column) indicating that the phase conductors are sequentially placed starting from the left side position.

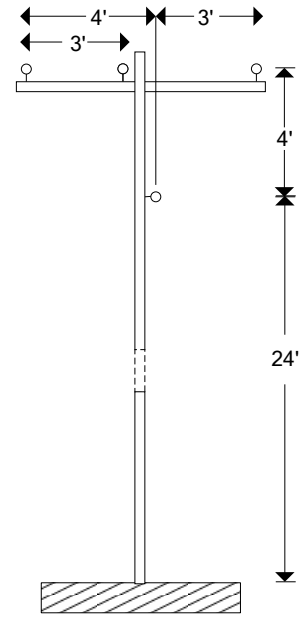


Figure A. Overhead line spacing for the IEEE 34-bus system

TABLE C. BRANCH DATA OF IEEE 34-BUS SYSTEM

Bus		Configuration	length (ft)	Line Conductor		Neutral Conductor	
From	To			R (Ω/mi)	GMR (ft)	R (Ω/mi)	GMR (ft)
800	802	BACN	2580	1.69	0.00418	1.69	0.00418
802	806	BACN	1730	1.69	0.00418	1.69	0.00418
806	808	BACN	32230	1.69	0.00418	1.69	0.00418
808	810	BCAN	5840	2.55	0.00452	2.55	0.00452
808	812	BACN	37500	1.69	0.00418	1.69	0.00418
812	814	BACN	29730	1.69	0.00418	1.69	0.00418
814	850	BACN	10	1.69	0.00418	1.69	0.00418
816	818	ABCN	1710	2.55	0.00452	2.55	0.00452
816	824	BACN	10210	1.69	0.00418	1.69	0.00418
818	820	ABCN	48150	2.55	0.00452	2.55	0.00452
820	822	ABCN	13740	2.55	0.00452	2.55	0.00452
824	826	BCAN	3030	2.55	0.00452	2.55	0.00452
824	828	BACN	840	1.69	0.00418	1.69	0.00418
828	830	BACN	20440	1.69	0.00418	1.69	0.00418
830	854	BACN	520	1.69	0.00418	1.69	0.00418
832	858	BACN	4900	1.69	0.00418	1.69	0.00418
832	888	BACN	100	1.69	0.00418	1.69	0.00418
834	860	BACN	2020	1.69	0.00418	1.69	0.00418
834	842	BACN	280	1.69	0.00418	1.69	0.00418
836	840	BACN	860	1.69	0.00418	1.69	0.00418
836	862	BACN	280	1.69	0.00418	1.69	0.00418
842	844	BACN	1350	1.69	0.00418	1.69	0.00418
844	846	BACN	3640	1.69	0.00418	1.69	0.00418
846	848	BACN	530	1.69	0.00418	1.69	0.00418
850	816	BACN	310	1.69	0.00418	1.69	0.00418
852	832	BACN	10	1.69	0.00418	1.69	0.00418
854	856	BCAN	23330	2.55	0.00452	2.55	0.00452
854	852	BACN	36830	1.69	0.00418	1.69	0.00418
858	864	ABCN	1620	2.55	0.00452	2.55	0.00452
858	834	BACN	5830	1.69	0.00418	1.69	0.00418
860	836	BACN	2680	1.69	0.00418	1.69	0.00418
862	838	ACBN	4860	1.69	0.00418	1.69	0.00418
888	890	BACN	10560	1.12	0.00446	1.12	0.00446

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