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Optimal Capacitor Placement in Radial Distribution Networks

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Abstract - Inserting capacitor banks in electrical distribution systems has many advantages on reducing the total power losses and improving the voltage profile for the system overall. In this paper a new method is developed for the determination of the optimal sizes and places of the required capacitor banks in order to maximize net present value (NPV). NPV is a criteria to evaluate the cost benefit of the projects. The developed method relies primarily on the careful selection of the operating limits of the key variables of the system. The method is simulated using ETAP 12.6 which depends on the Genetic Algorithm as an optimization technique. Simulation was done on IEEE-10 bus test system and on a practical distribution system of the Egyptian Ethylene Company. The simulation results show the effectiveness of the methods in reducing the total power losses. Also, they showed the success of it to rise the voltage at each bus, but by a small amount of enhancing. The capacitor bank can`t be the only way to increase the voltage from very low values to high values because of the reactive compensation limitation

Index Terms — Optimal Capacitor Placement; ; Reactive power compensation; Power Factor Correction; ETAP; voltage profile improvement; power losses reduction; net present value (NPV).

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1. INTRODUCTION

Reducing power system losses whether active or reactive is a basic target for many researches; the improvement of power factor of the system by using capacitor banks has a great impact on reducing these losses. But, it is important to determine the optimal sizes of these capacitors and their best locations in order to achieve the minimum value of the power losses. A lot of researches and optimization techniques had been done in this field.

Depending on Evolutionary Programming Algorithm (EP), MATLAB was used [1] to solve a multi-objective function to determine the optimal places of the capacitor banks in IEEE -33 bus system, the performance of the system was noticed without any capacitors, with one capacitor, and with two capacitors. Firefly algorithm (FA) method was used [2] to solve the same problem, the target of the simulation is to minimize the overall cost of the system, but for simplicity, the cost of operation and maintenance of the capacitor was neglected.

Improving the reliability was aimed depending on Bee Colony Optimization (BCO) algorithm [3], and the result ended to the reduction of emissions of carbon dioxide.

Genetic Algorithm (GA) was widely used with different simulation programs. MATLAB was used [4] on IEEE-14 bus and [5] on IEEE-69 bus system. Also, it was used based on Real Coded Genetic Algorithm [6] on IEEE-33 bus system considering the effect of increasing the iteration number of the algorithm on power loss reduction. ETAP was used as a simulator [7] on IEEE-60 bus test system. In [8] Results of ETAP on IEEE 10 bus system were compared with those obtained using fuzzy algorithm. Considering the existence of harmonics due to non-linear loads, optimal capacitor placement was implemented [9], where measuring total harmonic distortion (THD) as an indication index showed the effect of the harmonics.

Non-Dominated Sorting Genetic Algorithm II (NSGA-II) [10] was utilized using MATLAB. Mi.-Power was used [11] on 11-kV network in Jaipur city which is about 2600-bus system.

Mixed-integer programming (MIP) was presented [12] to allocate capacitors on the low side of a transformer to decrease the power loss by maximize the net present value (NPV).

Many solutions were introduced using Particle Swarm Optimization (PSO) algorithm and its modifications. It was combined with Loss Sensitivity factors [13] on Tabriz distribution system in Iran. Hybrid Particle Swarm Optimization (HPSO) [14] combined with Fuzzy Expert System (FES) were applied on IEEE 34-bus system. Improved Binary PSO (IBPSO) [15] was used on IEEE -16, IEEE 33-bus systems.

In this paper, the optimal capacitor placement will be achieved using ETAP 12.6 on IEEE-10 bus test system and the obtained results are compared to those obtained in [8]. Also, a practical distribution system of Egyptian Ethylene Company is used to prove the capability of this method. The net present value (NPV) is used to evaluate the cost benefit of the systems. The difference between the two systems is that the first one has a low voltage value at the farthest bus. This study proves that the capacitor banks can mitigate the voltage drop but not overcome it totally. With the target of achieving maximum NPV over the project life cycle, the optimal operating limits of both voltage and targeted power factor constraints will be determined. In all previous works these limits were inserted to the program without being linked to the overall profit of the system

This paper is organized as follows: the detailed problem modeling and formulation is explained in section II. In section III, the case study, simulation results, and related discussion are illustrated. Section IV concludes the achievements of this study based on the simulation results.

2. PROBLEM FORMULATION AND METHODOLOGY

The problem is determining the optimal places and sizes of the capacitor banks to obtain the decrease power loss, improve the voltage profile, and to achieve the maximum NPV.
For any connected two buses (i) and (i+1) shown in Fig. (1):

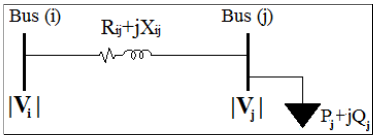

Fig.1. Two buses connected together

The active and reactive power losses of the branch between them [16] can be expressed using equations (1) and (2) respectively:

$$P_{Loss\ (ij)} = R_{ij} \cdot \frac{P_j^2+Q_j^2}{|V_j|^2} \quad (1)$$

$$Q_{Loss\ (ij)}=X_{ij} \cdot \frac{P_j^2+Q_j^2}{|V_j|^2} \quad (2)$$

Where: $P_{Loss\ (ij)}$, $Q_{Loss\ (ij)}$ are the active and reactive power losses on the branch between bus (i) and (j), respectively.

R_{ij} , X_{ij} are resistance and reactance of the branch between bus (*i*) and bus (*j*), respectively.

The voltage drop between two buses is expressed as follows:

$$\Delta V_{ij}= (R_{ij} + X_{ij}).\frac{P_j-jQ_j}{V_i} \quad (3)$$

The voltage magnitude at each bus is obtained from:

$$V_j= V_i - \Delta V_{ij} \quad (4)$$

Where: V_i : Voltage magnitude at bus (i).
V_j : Voltage magnitude at bus (j).
P_j , Q_j: The active and reactive power at bus (j).

The total reduction in kVA when using the capacitor bank is given by [8] and calculated from eq. (5)

$$S\ (reduction) = \frac{P}{\cos\varphi_1} - \frac{P}{\cos\varphi_2} \quad (5)$$

The total amount of reactive power needed to compensate is given by [8] and calculated from eq. (6)

$$Q_{reduction} = P * (\tan\varphi_1 - \tan\varphi_2) \quad (6)$$

Where P : Total active power of the system
φ_1: is the angel corresponding to power factor before correction.
φ_2: is the angel corresponding to power factor after correction.

The total amount of compensation (injected reactive power) to the system mustn`t exceed the total reactive power absorbed by it to prevent the overcompensation problem [17]. This can be illustrated by the following equation:

$$Q_C^{Total} < Q_L^{Total} \quad (7)$$

Where Q_C^{Total} : Total reactive power injected to the system
Q_L^{Total} : Total reactive power absorbed by the system.

Voltage rise at the bus after capacitor installation can be illustrated in [18] and calculated from equation (8):

$$\frac{\Delta V}{V} = \frac{X.Q}{V^2} \quad (8)$$

Where X is the total branch reactance from this bus to the source, Q is capacitor bank (MVAR),x_i: 0 or 1, 1 means a capacitor is connected to bus or not.

Generally, the voltage rise at the farthest bus due to capacitor installation is calculated as follows:

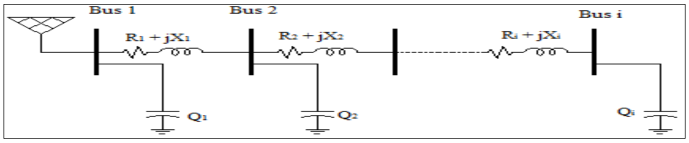

Fig.2. Radial distribution system

$$\frac{\Delta V}{V}\Big|_{bus\ (i)} = \frac{\sum_{k=1}^{i}\sum_{j=1}^{k} x_i.Q_k.X_j}{V^2} \quad (9)$$

Which means that the voltage rise at the farthest bus is limited by the reactive compensation constraint according to eq. (7).

The solution for this problem is done using Optimal Capacitor Placement (OCP) module in ETAP 12.6 tool to determine the optimal places and sizes of the capacitor units. The OCP module depends on Genetic Algorithm (GA) [19]. GA is an optimization technique which is inspired by the natural selection theory, with generation of solutions with wide diversity in order to represent the characteristics of the whole searching space. By mutation and crossover, good characteristics can be selected and then carried to the next generation. The optimal solution can be obtained through repeated first generations. GA is considered a strong competitive for the other recent optimization techniques, for instance the particle swarm optimization (PSO). GA is easy to implement, determines values which are closer to the known values than does PSO, so it is superior to the particle swarm PSO [20]. Also, GA reaches the solution faster than PSO, and the major advantage of the GA is that the solution is globally optimal [21].

The objective function in this model is the overall cost of the system [19]. This overall cost consists of:

- Purchasing cost of the capacitor banks.
- Installation cost of these banks.
- Annual cost of operation and maintenance for them.
- The cost of the loss energy of the system.

The cost equation can be expressed as follow:

$$\text{Minimize}\sum_{i=1}^{N_{bus}}(x_iC_{0i} + Q_{ci}C_{1i} + B_iC_{2i}T) + C_2\sum_{l=1}^{N_{load}} T_lP_L^l \quad (8)$$

Where:
N_{bus}: Number of buses in the system.
x_i : 0or1, 1 means a capacitor is connected to bus or not.
$C_{0\,i}$: Installation cost of the capacitor.
$Q_{C\,i}$: Size of the capacitor bank (kVAR).
$C_{1\,i}$: Purchasing cost of 1 kVAR.
B_i : Number of capacitor banks.
C_{2i} : Operation and maintenance cost (per year).
C_2 : Cost of energy losses (per KW-hr).
P_L^l : Power loss at load demand (*l*).
T_l : Time duration of load level (*l*).
T : Planning time (years).

Subjected to the following constraints:

$$V_{min} \le V \le V_{max} \quad (9)$$

$$PF_{\ min} \le PF \le PF_{\ max} \quad (10)$$

Net Present Value (NPV): is the difference between the cash inflows and the present value of cash outflows, it is the indication of the profitability of the project. If it is positive, means the project will add a value to the utility, otherwise, the loss will be the result. Simply, NPV discounts each year's cash flow back to the present and then deducts the initial investment, giving a net value of the project in today's dollars [12]. NPV can be calculated from eq. (11).

$$NPV = \sum_{t=1}^{T} \frac{B_t}{(1+d)^t} - IO \qquad (11)$$

Where: B_t net cash inflows in the t^{th} year, which is the difference between the loss reduction and operating and maintenance of capacitors in this year.

$$B_t = \left(\left(P_{Loss\,(before)} - P_{Loss\,(after)}\right) * 8760 * C_2\right) - \sum_{i=1}^{N_{bus}} X_i * C2i * B_i \qquad (12)$$

Where: IO is the initial investment outlay of cash which is installation and purchasing cost.

$$IO = x_i C_{0i} + Q_{ci} C_{1i} \qquad (13)$$

r : Discount (Interest) rate.
$P_{Loss\,(before)}$: Power loss of system without capacitors.
$P_{Loss\,(before)}$: Power loss of system with capacitors.

The main steps of the proposed framework are shown in Fig.1. Firstly, the steps start with inserting system data. Secondly, power flow calculations are performed to determine the total power losses, voltage drop according to eq`s 1, 2, 3, 4 without capacitors. Thirdly, use the OCP module many times to determine the optimal capacitors. In each time change the voltage limits and the target power factor according to eq`s 8, 9, 10. Each case of voltage limits can be called as a voltage combination. The case that causes over compensation is rejected according to eq. 7. Then, in each time determine the power losses according to equations 1, 2, and NPV according to eq.12.Finally, chose the case that achieves the maximum NPV.

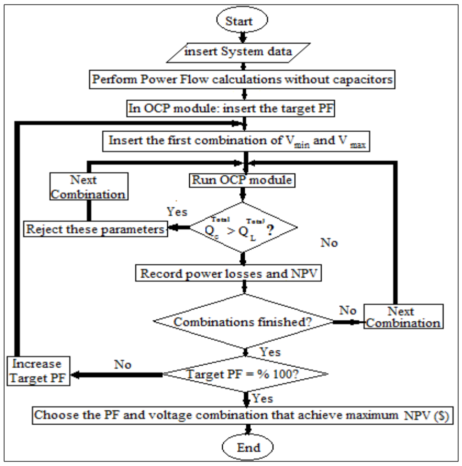

Fig.3. Flow chart for the proposed framework

3. SYSTEM ANALYSIS AND RESULT DISCUSSION

3.1.1. APPLYING THE PROPOSED METHOD ON A TEST SYSTEM

23 kV, IEEE-10 bus test system is chosen for simulation, the single line diagram (SLD) is shown in Fig.2. The load is considered fixed. The data of the system is obtained from [**22**] and is shown in table.1.

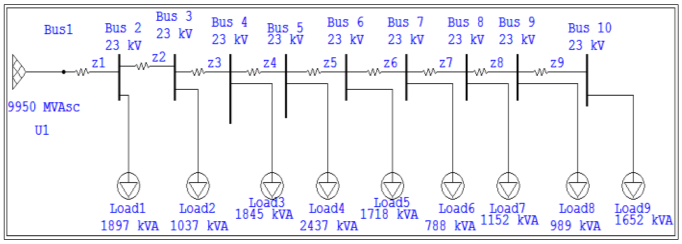

Fig.4. IEEE-10 bus test system

TABLE.1
IEEE-10 BUS SYSTEM DATA

Load data at each bus				Branch impedance between buses				
Bus	P kW	Q kVAR		Z	Bus i	Bus i+1	$R_{i,i+1}$	$X_{i,i+1}$
2	1840	460		Z_1	1	2	0.1233	0.4127
3	980	340		Z_2	2	3	0.014	0.6057
4	1790	446		Z_3	3	4	0.7463	1.2050
5	1598	1840		Z_4	4	5	0.6984	0.6084
6	1610	600		Z_5	5	6	1.9831	1.7276
7	780	110		Z_6	6	7	0.9053	0.7886
8	1150	60		Z_7	7	8	2.0055	1.1640
9	980	130		Z_8	8	9	4.7943	2.1760
10	1640	200		Z_9	9	10	5.3434	3.0264

On the basis of 0.04 $/kW-hr cost of the energy loss and consider all the system`s buses as possible candidates to connect the capacitor banks. Cost of purchasing and installation together is 30 $/kVAR for MV capacitor and 25 $/kVAR for LV capacitor cost [23], annual cost for operating and maintenance is 100 $/Bank, and 50 $/ Bank for MV and LV capacitors, respectively. Consider %10 interest rate, and the life expectancy of the capacitors is 10 years. Run the OCP module in ETAP 12.6 software many times and in each time, change limits of the voltage constraint, and the value of target power factor constraint. Reject all values that cause over compensation according to eq. (7). NPV for the rest cases are shown in the table.2.

TABLE.2
NET PRESENT VALUE (NPV) VS. DIFFERENT LIMITS OF TARGET PF AND PU VOLTAGES

Case	Inserted values to ETAP			NPV ($)
	Target PF	V_{min}	V_{max}	
1	95%	0.87	1.05	144,084.20
2	95%	0.87	1.03	141,127.20
3	95%	0.87	1.02	142,498.83
4	95%	0.87	1.01	149,055.38
5	95%	0.87	1	140,296.59
6	96%	0.87	1.05	141,769.57
7	96%	0.87	1.01	146,197.19
8	96%	0.87	1	140,859.24
9	97%	0.87	1.05	142,123.03
10	97%	0.87	1.04	146,092.57
11	97%	0.87	1.01	146,671.19
12	98%	0.87	1.04	139,882.49
13	98%	0.87	1.02	136,889.69

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From the previous results, it is clear that selection of the target power factor and limits of voltage constraint has an effect on the net present value (NPV).

For our system here, we will select the values of parameters at which the maximum NPV is achieved which is Case (4).

It is worth to be mentioned that if the selected case is compared to the case (13) (i.e. minimum NPV), it is shown that case (4) adds profitability to the utility more than case (13) by % 9.

TABLE.3

OPTIMAL PLACES AND SIZES OF CAPACITOR BANKS

Bus Number	Number of Banks	Total kVAR
2	1	100
3	1	100
5	16	1600
6	10	1000
7	1	100
8	1	100
9	4	400
10	3	300
Total	37	3700

Table 4 shows the comparison of the obtained results to those obtained in [8] which depended on random insertion of the constraints` values without linking them with the maximum profit.

TABLE.4

COMPARISON OF THE OBTAINED RESULTS

	No Compensate	ETAP with random limits [8]	Proposed
kW loss	783.9	702.7	691.7
% kW Loss reduction	-	10.34	11.76
kVAR loss	1036.9	914	900.7
% kVAR Loss reduction	-	11.86	13.14
Total kVAR placed	-	3283	3700
Minimum voltage	0.8375	0.8623	0.8722
Annual Cost ($)	274,678	246,226	242,371
Annual Capacitor operation cost ($)	----------	4,557	3,700
Annual Saving ($)	----------	23,895	28,607

The proposed technique achieves its desired targets of reducing the total power losses of the system, money saving, and improving the voltage profile of the system overall.

Although the minimum voltage increased after capacitor installation, but 0.8722 Pu as a minimum voltage of the system can`t be acceptable in the practical power systems. To rise the voltage more than this value, it needs a lot of capacitor banks (i.e. over compensation for the reactive power) and this can`t be allowed as it will make the system has a lead power factor which has a lot of problems. For instance, to increase the minimum voltage from 0.8375 PU to 0.95 PU, then 12,600 kVAR are required (i.e. over compensation), and hence the total losses will be 885.9 kW which means that the losses increased after installation the capacitors instead of decreasing it.

3.1.2. APPLYING THE PROPOSED METHOD ON A PRACTICAL SYSTEM

Case study: A practical power distribution system is the substation of Egyptian Ethylene Company, which consists of 11 kV bus fed from a power plant through 66/11 kV 50 MVA transformer. 6.6 kV loads fed from 6.6 kV buses that are fed from 11 kV bus through 2 transformers each one is 5.5 MVA, and 400 V loads that are fed from 6 transformers 11/0.4 kV, 2.5 MVA for each. Single line diagram and data of system are shown in Fig.2 and tables 5, 6, 7, respectively.

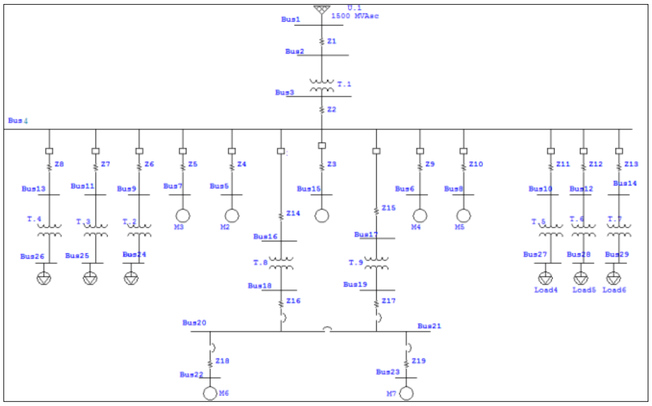

Fig.5. 29-bus Egyptian Ethylene Company distribution System

TABLE5.LOAD DATA

Load data at each bus		
Bus	P kW	Q KVAR
5	1,150	557
6	1,150	557
7	5,600	3023
8	5,600	3023
15	1,760	852.4
22	1,740	939.2
23	1,740	939.2
24	1,350	653.8
25	1,350	653.8
26	1,350	653.8
27	1,350	653.8
28	1,350	653.8
29	1,350	653.8
Tot.	26,840	13,813

TABLE.6. BRANCH DATA

Branch data from between buses				
Z	Bus (i)	Bus (i+1)	$R_{i,i+1}$	$X_{i,i+1}$
Z1	1	2	0.097	0.144
Z2	3	4	0.04	0.102
Z3	4	15	0.065	0.032
Z4	4	5	0.196	0.096
Z5	4	7	0.099	0.087
Z6	4	9	0.196	0.128
Z7	4	11	0.196	0.128
Z8	4	13	0.196	0.128
Z9	4	6	0.196	0.096
Z10	4	8	0.099	0.087
Z11	4	10	0.196	0.128
Z12	4	12	0.196	0.128
Z13	4	14	0.196	0.128
Z14	4	16	0.159	0.124
Z15	4	17	0.159	0.124
Z16	18	20	0.196	0.125
Z17	19	21	0.196	0.125
Z18	20	22	0.03	0.16
Z19	21	23	0.03	0.16

TABLE.7
TRANSFORMERS` DATA

Transformer	Ratio	MVA	%Z
T.1	66/11	50	9.89
T.2	11/0.4	2.5	6.6
T.3	11/0.4	2.5	6.6
T.4	11/0.4	2.5	6.6
T.5	11/0.4	2.5	6.6
T.6	11/0.4	2.5	6.6
T.7	11/0.4	2.5	6.6
T.8	11/6.6	5.5	7.1
T.9	11/6.6	5.5	7.1

Depending on the same cost data in case (1), the load is considered fixed. The candidate buses for allocate capacitors are 11kV and 400V buses. Reject cases that cause over compensation, the effect of changing the limits of voltage and PF on NPV are shown in table.8.

TABLE.8
NET PRESENT VALUE (NPV) VS. DIFFERENT VALUES OF TARGET PF AND PU VOLTAGES

Case	Inserted values to ETAP			NPV ($)
	Target PF	V_{min}	V_{max}	
1	0.95	0.95	1.05	170,608.02
2	0.95	0.95	1.04	142,535.78
3	0.95	0.95	1.03	154,324.70
4	0.95	0.96	1.05	170,608.02
5	0.95	0.96	1.04	128,644.22
6	0.95	0.96	1.03	125,301.35
7	0.96	0.95	1.05	156,326.85
8	0.96	0.95	1.04	151,943.00
9	0.96	0.95	1.03	164,782.90
10	0.96	0.96	1.05	123,938.39
11	0.96	0.96	1.04	135,575.95
12	0.96	0.96	1.03	135,951.01
13	0.97	0.95	1.05	149,998.49
14	0.97	0.95	1.04	138,232.33
15	0.97	0.95	1.03	168,613.78
16	0.97	0.96	1.05	149,998.49
17	0.97	0.96	1.04	138,232.33
18	0.97	0.96	1.03	152,719.77
19	0.98	0.95	1.05	137,956.50
20	0.98	0.96	1.05	137,956.50

Similarly, maximum NPV is selected that can be achieved by case (4). Table.9 shows the optimal places and sizes of capacitor banks obtained in this case.

TABLE.9
OPTIMAL PLACES AND SIZES OF CAPACITOR BANKS

Bus Number	Number of Banks	Total kVAR
5	3	300
6	5	500
7	18	1,800
8	20	2,000
10	7	700
12	1	100
15	9	900
16	2	200
18	8	800
22	7	700
23	11	1,100
24	4	400
25	9	900
26	5	500
27	4	400
28	4	400
29	5	500
Total	122	12,200

If this case is compared to case (10) (i.e. minimum NPV), it is Shown that case (4) adds profitability to the utility more than case (10) by % 37.

TABLE.10
COMPARING BEFORE AND AFTER CAPACITOR BANKS

	Without Compensation	With Compensation
kW loss	708	517.7
% kW Loss reduction	-	26.88
kVAR loss	3963.4	2882.2
% kVAR Loss reduction	-	27.4
Minimum voltage (pu.)	0.920044	0.9601
Annual Cost ($)	248,083	181,402
Annual Capacitor operation cost ($)	-----------	10,650
Net Yearly Profit ($)	-----------	56,031

4. CONCLUSION

This paper provides a methodology for determining the optimal places and sizes of the capacitor units in the radial distribution system. This way makes saving in the total lost energy, while improving the voltage profile of the system overall. The proposed way utilizes ETAP software which depends on Genetic Algorithm. The results have shown that values of constraints of the objective function (i.e. voltage and power factor for the buses) can`t be done randomly. Net present value (NPV) is used to compare the cost benefit of the system at different values of these constraints. Inserting different values of these constraints affect sizes and places of the capacitors, and therefore affect the NPV of the system.

Also, results showed that although improvement of voltage profile is one of the great achievements of power factor correction, but it can`t raise the very low value of voltage at the farthest bus of the radial system. The voltage improvement is usually limited by the maximum reactive power injected to the system (i.e. over compensation is forbidden) as shown in eq. (8). The fixation of the large voltage drop isn`t the role of the capacitor banks only, they only help to mitigate it but not vanish it totally.

It is worth to mention that the large voltage drop can be overcome by cooperation of many factors, like increasing cross-sectional areas of the branches, adjusting the transformers` taps…etc.

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