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A Proposed Algorithm for Reactive Power & Voltage Coordination in Distribution Systems Using Fuzzy Technique

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Abstract

This method finds the Under Load Tap Changer (ULTC) position and capacitor ON/OFF status of each hour for the next day in main or secondary distribution substations, so the secondary bus voltage improves and the reactive power flow into the transformer can be restrained at the same time. The only condition to achieve these goals is the previous knowledge (by forecasting) of load demand for active and reactive power and the primary bus voltage for each hour of that day. The practical constraints are involved through the use of membership concept in fuzzy set theory, where these constraints are bus voltage limits, the tolerable worst power factor & the maximum allowable number of switching operations for the Load Tap Changer (LTC) and capacitor in a day. This method is also considering the variation of load active & reactive power with its voltage, where the loads are classified into three categories according to their relationship with voltage, and so there are constant impedance loads, constant current loads and constant power loads. To demonstrate the usefulness of this method an example on one of the Iraqi national grid substations (132/33KV Yarmook substation) was made in MATLAB.

Keywords: Reactive power/voltage control; Shunt capacitor; Tap changing transformer; Fuzzy logic; Dynamic programming; Distribution system.

خوارزمية مُقترحة لتنسيق القدرة المتفاعلة و الفولتية في منظومات التوزيع باستخدام التقنية المضببة

الخلاصة

تجد هذه الطريقة موقع مُغير الفولتية تحت الحمل وحالة اشتغال أو إطفاء المكثف لكل ساعة من اليوم التالي في محطات التوزيع الرئيسية أو الثانوية, وهكذا تتحسن الفولتية و تُقنن القدرة المتفاعلة المارة بالمحولة في الوقت نفسه . الشرط الوحيد لتحقيق هذه الأهداف هو المعرفة المسبقة (باستخدام التنبؤ) بمقدار طلب الحمل من القدرة الفعالة والمتفاعلة وفولتية الملف الأبتدائي للمحولة لكل ساعة من ذلك اليوم. المحددات العملية يتم تضمينها من خلال استعمال مفهوم العضوية في نظرية المجموعة المضببة , حيث أن هذه المحددات هي حدود الفولتية , أسوء معامل قدرة مسموح به و أقصى عدد مسموح به من عمليات تغيير موقع مُغير الفولتية تحت الحمل والمكثف في اليوم الواحد. وكذلك تأخذ هذه الطريقة بنظر الاعتبار تغير الحمل كقدرة فعالة و متفاعلة مع فولتيته , حيث تصنف الأحمال إلى ثلاث فئات طبقاً لعلاقتها مع الفولتية , وهكذا هناك أحمال الممانعة الثابتة , أحمال التيار الثابت و أحمال القدرة الثابتة . لغرض التوضيح المفصل عن فائدة هذه الطريقة تم عمل مثال على واحدة من محطات الشبكة الوطنية العراقية (محطة اليرموك 132\33 ك.ف.) باستخدام ال MATLAB.

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1. Introduction

The recent distribution systems are more complicated under deregulated environment. From a standpoint of cost and reliability, the solution quality becomes much more important in handling distribution systems. To improve the performance of distribution systems, distribution automation has been carried out to smooth operation and planning. As a gamework of distribution automation, state estimation, service restoration, voltage and reactive power control, etc., have been undertaken.

As distribution networks become larger, voltage and reactive power control requires more computational effort, thus, a fast and efficient method is needed to smooth voltage and reactive power control in distribution systems. Many approaches have been used, Yutian Liu [1] proposed a simplified dynamic programming and a fuzzy logic control algorithm to deal with the two sub-problems, substation level and feeder level respectively. Qi Xiaoman [2] presented a novel comprehensive VQC control technology. With the help of high-performance MCU, it implements adaptive prediction of electrical parameters, and then Fuzzy Logic is applied to optimize the control strategy. XU Yan [3] used the fuzzy logic controller in power station reactive power integrated control, the simulation is implemented with MATLAB and PASAP. In Ruey's[4] paper , the reactive power and voltage control problem was first formulated with fuzzy sets then an annealing searching technique is used to find a proper combination of Load Tap Changer positions and capacitors ON/OFF switching operations in a day. Shu Hongchun [5] work proposed a new method to extract the fuzzy rules using rough set theory. The method was applied to obtain fuzzy control rules for substation voltage and reactive controller. Even lacking experience in the method. W. Zhang [6] presented in their paper an application of a Fuzzy Logic Controlled Particle Swarm Optimization (FLCPSO) to reactive power and voltage control (Volt/VAR control or VVC) considering voltage stability. An improved particle swarm optimization with three fuzzy controllers based on some heuristics is proposed to adaptively adjust the parameters of Particle Swarm Optimization (PSO).

In the present work, a Fuzzy Dynamic Programming (FDP) method which takes the practical constrains on secondary bus voltages and power factor of a main transformer and maximum allowable number of switching operations in a day for the LTC and capacitor into account is developed. Coordination of ULTC and capacitor is achieved through the maximization of a fuzzy objective function (which is the sum of a fuzzy membership functions).

2. System Configuration

The 132/33KV distribution substation is shown in Fig. 1, it consists of a 132KV primary bus, a 33KV secondary bus and a main transformer. The main transformer is equipped with Under Load Tap Changer (ULTC) to keep the secondary bus voltage nearly its specified value under changing load conditions. This is accomplished with eleven taps on each side of nominal settings. In addition, a capacitor is installed at the 33KV secondary bus which supplies power to the distribution feeders. The capacitor must be switching ON/OFF according to system reactive power demand such that the reactive power flow into the main transformer is minimized. The basic idea behind this is that it is not necessary for the distribution substation to take much reactive power form the subtransmission and transmission system if the reactive power flow into each transformer at substation is kept minimal. The power factor of the substation can be improved and the reactive power flow and losses on the subtransmission and transmission lines can also be reduced.

3. Mathematical Model for A Distribution Substation

To estimate the voltage change when the capacitor is switched ON/OFF and to find the transformer voltage ratio when the ULTC movement is needed, the mathematical model for the substation of Fig. 1 is illustrated in Fig. 2. The main transformer resistance and its magnetizing admittance are neglected in the present study.

Note the following symbols which are used in Fig. 2 :

V_1 = main transformer primary bus voltage (132KV)
V_2 = main transformer secondary bus voltage (33V)
Z_T = main transformer impedance
$\boldsymbol{t}$ = transformer voltage ratio
P_L = real power load demand
Q_L = reactive power load demand
Q_C = reactive power injected by the capacitor
$\boldsymbol{Z_C}$ = the capacitor impedance
$\boldsymbol{S_L = P_L + j\,Q_L}$

In practical, the real and reactive power demands will change as the main transformer secondary bus voltage is changed. Three kinds of load models for static load have been used to describe the relationship between the load demand and bus voltage.

The ***ZIP*** model (constant impedance, constant current and constant power) is widely used to express the load demands as functions of bus voltages (as shown in Eq.s 1 & 2) where P_o and Q_o represent the active and reactive power demands when the transformer secondary bus voltage is kept 1.0 p.u. & V is the ratio of the operation voltage to the nominal voltage. The proportional coefficients for the three kinds of load models are expressed as (a, b, c) and (d, e, f) for real power and reactive power demand respectively [7].

$$P=P_o\,[\,a\,V^2 + b\,V + c\,] \qquad \ldots (1)$$

$$Q=Q_o[\,d\,V^2 + e\,V + f\,] \qquad \ldots (2)$$

To control the tap position of the ULTC it is necessary to find the main transformer voltage ratio ($\boldsymbol{t}$) through mathematical equations as a function of all variables, so the load real & reactive power equations will be :

$$P_L = \frac{|V_1||V_2|}{|Z_1|}\sin d \qquad \ldots (3)$$

$$Q_L = \frac{|V_1||V_2|}{|Z_1|}\cos d - \frac{|V_2|^2}{|Z_1|} - \frac{|V_2|^2}{|Z_2|} - \frac{|V_2|^2}{|Z_3|} \qquad \ldots (4)$$

where

$$Z_1 = \frac{|Z_T|}{t}$$

$$Z_2 = \frac{|Z_T|}{1-t}$$

$$Z_3 = -Z_C$$

Now, let

$$\frac{1}{|Z|} = \frac{1}{|Z_1|} + \frac{1}{|Z_2|} + \frac{1}{|Z_3|}$$

Then

$$\frac{1}{|Z|} = \frac{t}{|Z_T|} + \frac{1-t}{|Z_T|} - \frac{1}{|Z_C|}$$

$$= \frac{|Z_C|-|Z_T|}{|Z_T||Z_C|}$$

And for the case when the capacitor is switched-OFF

$$\frac{1}{|Z|} = \frac{t}{|Z_T|} + \frac{1-t}{|Z_T|} = \frac{1}{|Z_T|}$$

So, we write

$$|Z| = K\,|Z_T| = X \qquad \text{...(5)}$$

when the capacitor is switched-ON

$$k = \frac{|Z_C|}{|Z_C|-|Z_T|}$$

and when the capacitor is switched-OFF

$$k = 1$$

Now the Eq.s 3 and 4 will be

$$P_L = \frac{t\,|V_1||V_2|}{|Z_T|}\sin d \qquad \text{...(6)}$$

$$Q_L = \frac{t\,|V_1||V_2|}{|Z_T|}\cos d - \frac{|V_2|^2}{k\,|Z_T|} \qquad \text{...(7)}$$

By combining Eq. 6 with Eq. 7 and square them, we have

$$\left[Q_L + \frac{|V_2|^2}{k\,|Z_T|}\right]^2 = \left[\frac{t\,|V_1||V_2|}{|Z_T|}\right]^2 - P_L^2 \qquad \text{.....(8)}$$

Substituting (1) and (2) into (8) , we have :

$$A|V_2|^4 + B|V_2|^3 + [C-(k\,.\,\boldsymbol{t}\;|V_1|)^2]\,|V_2|^2 + D\,|V_2| + E = 0 \qquad \text{...(9)}$$

Where

$A=1+2d\,X\,Q_o+a^2X^2P_o^2 + d^2X^2Q_o^2$

$B= 2eX\,Q_o+2\,e\,X^2P_o^2 + 2\,d\,e\,X^2Q_o^2$

$C= 2\,f\,X\,Q_o + (2ac + b^2)\,X^2P_o^2 + (2\,d\,f + e^2)\,X^2Q_o^2$

$D= 2\,b\,c\,X^2P_o^2 + 2\,e\,f\,X^2Q_o^2$

$E= c^2X^2P_o^2 + f^2X^2Q_o^2$

The transformer voltage ratio can be derived from (9)

$$\boldsymbol{t} = \left(\frac{1}{k^2\,|V_1|^2|V_2|^2}\Big[A|V_2|^4 + B|V_2|^3 + C\,|V_2|^2 + D|V_2| + E\Big]\right)^{1/2} \qquad \text{...(10)}$$

The ideal transformer voltage ratio $\boldsymbol{t}_{\textit{ideal}}$ computed when the specified voltage $|V_2|$ is substituted into (10) is not the actual transformer voltage ratio $\boldsymbol{t}_{\textit{actual}}$ we want because $\boldsymbol{t}_{\textit{actual}}$ is rated to

LTC tap position TAP as follows :

$$t_{actual} = 1 \pm 0.01 \times TAP \qquad ...(11)$$

where *TAP* is an integer .

To reach the actual transformer ratio t_{actual} we first find an integer TAP such that (1 + 0.01 × *TAP*) is closest to t_{ideal}. Then t_{actual} is computed from Eq. 10. Finally, the actual $|V_2|$ that is adjusted by moving ULTC can be found by substituting t_{actual} into Eq. 9.

4. The Application of Fuzzy Set Theory on the Reactive Power/Voltage Control

In practice, the operators at the distribution substation control center tend to use some heuristic rules based on their past experience to determine a proper dispatching strategy. For example, the transformer power factor must be kept as high as possible, secondary bus voltage deviation from the specified value must be maintained as small as possible and the number of switching operations for ULTC movements and capacitor circuit breaker in a day must not exceed 30 and 6, respectively, (the total number of switching operations should be kept minimal).

The heuristic rules are expressed in imprecise linguistic expressions. For example, the terms **“as high as possible”, “as small as possible”, “kept minimal”** are used in these rules. However, these ***linguistic variables*** are rather imprecise (The concept of ***linguistic variables*** is fundamental within fuzzy set theory. Informally, a ***linguistic variable*** is a variable whose values are words or sentences rather than numbers [8]).

To be specific how small is “small”? it is obvious that these rules with imprecise linguistic expressions can not be included in calculations. To model the rules mentioned above fuzzy sets are employed. Fuzzy sets are used to model the uncertainty in a simple nonlinear framework.

5. Fuzzy Dynamic Programming (FDP) Method

With the mathematical model for reactive power/voltage control in section 3 at hand, the change in secondary bus voltage due to capacitor switching can be estimated. It is also able to estimate the desired TAP position using the Eq. 11. Using (10) and (11) to reach the desired tap position TAP_i (i = 1, …, 24) hour by hour, there will be two major problems. First of all, it is needed to know in advance the ON/OFF status of the capacitor at each hour. Of course, the capacitor can be dispatched using the simple rule that the capacitor is switching ON/OFF when the lagging/leading reactive power flow into the transformer exceeds 50% of the capacitor rated capacity. However the coordination between capacitor switching and tap movements is impossible in this case. Secondary, it may turn out that the taps are moved too often based on Eq.s 10 and 11. That means it is possible to exceed the limits of the number of movements for ULTC in a day by using the Eq.s 10 and 11 to determine the tap position at each hour. The same consideration may happen to total switching number of capacitor in a day.

To resolve the difficulty, a fuzzy dynamic programming method is proposed to find a proper dispatching strategy for capacitor switchings and tap movements such that satisfactory secondary bus voltage profile and transformer power factor are reached. Hard limits on maximum allowable number of capacitor switchings and tap movements and bounds on secondary bus voltage and transformer power factor are also imposed [9].

To formulate the above-mentioned reactive power/voltage control problem in mathematical expressions, there is some definitions :

$Zc_{\,i}$ = 1, when capacitor is ON at hour $\boldsymbol{i}$

$Zc_{\,i}$= 0, when capacitor is OFF at hour $\boldsymbol{i}$

In addition to :

$|\Delta V_{2\,i}|$=secondary bus voltage deviation from the specified value at hour $\boldsymbol{i}$

$\underset{\sim}{\mu}_{|\Delta V_{2\,i}|}$= membership function for $|\Delta V_{2\,i}|$ at hour $\boldsymbol{i}$

$pf_{\,i}$ = transformer power factor at hour $\boldsymbol{i}$

$\underset{\sim}{\mu}_{pf}$ = membership function for pf at hour $\boldsymbol{i}$

N_{tap}= total switching number of LTC in a day

$\underset{\sim}{\mu}_{N\,tap}$ = membership function for N_{tap}

Nc = total switching number of capacitor in a day

$\underset{\sim}{\mu}_{Nc}$ = membership function for Nc

$TAP_{\,i}$=LTC tap position at hour $\boldsymbol{i}$

$|V_2\text{ min}|$=secondary bus voltage lower limit (0.95)

$|V_2\text{ max}|$=secondary bus voltage upper limit (1.05)

Now the reactive power/voltage control problem can be stated as an optimization over the study period (24 hours). So it is necessary to find a set of control variables $Zc_{\,i}$ ($\boldsymbol{i}$ = 1, …, 24) for the capacitor and TAP_i ($\boldsymbol{i}$ = 1, …, 24) for the LTC, so the objective function J will be:

$$J=\sum_{i=1}^{24}\underset{\sim}{\mu}_{|\Delta V_{2\,i}|}+\sum_{i=1}^{24}\underset{\sim}{\mu}_{pf_i}+\underset{\sim}{\mu}_{N_{tap}}+\underset{\sim}{\mu}_{N_C}$$

$$J = J_1 + J_2 + \underset{\sim}{\mu}_{N_{tap}} + \underset{\sim}{\mu}_{N_C} \;\ldots\;\ldots.(12)$$

It is maximized subject to

$$N_{tap}=\sum_{i=1}^{24}|TAP_i-TAP_{i-1}| \le 30 \quad \ldots(13)$$

$$Nc = \sum_{i=1}^{24}|Zc_i-Zc_{i-1}| \le 6 \quad \ldots(14)$$

$$|V_2\text{ min}| \le |V_2| \le |V_2\text{ max}| \quad \ldots(15)$$

$$|\,pf_I\,| \ge 0.8 \quad \ldots(16)$$

Note that the first term in the objective function (J_1) is to maintain the secondary bus voltage $|\,V_2\,|$ as close to the specified value as possible at all hours in the day. Just as in [10], the degree of satisfaction with the secondary bus voltage is described by a membership function $\mu_{|\,\Delta V_2\,|}$ for the fuzzy variable $\underset{\sim}{|\,\Delta V_2\,|}$. Detailed descriptions on the membership function will be given in the section 6. The secondary term J_2 in the objective function is to keep the power factor at the transformer as high as possible. Again, the membership function $\underset{\sim}{\mu}_{pf}$ gives the degree of satisfaction with the power factor. The main reason we put the third term μ_{Ntap} and the fourth term

μ_{Nc} in the objective function is making the number of tap movements and capacitor switchings minimum. As for the hard limits, the number of tap movements in a day is limited to be less than 30 in (13). And also the number of capacitor switchings in a day is limited to be less than 6 in (14). The bounds on secondary bus voltage and transformer power factor are described in (15) and (16), respectively.

With the mathematical expression in Eq.s (12−16) and membership functions (in the section 6), we can proceed to determine the desired control variables $Z_{c\,i}$ (i = 1, …, 24) for the capacitor and TAP_i (i = 1, …, 24) for the ULTC. First, the study period is divided into N stages (N = 24 for the present work). Since there are two possible values for $Z_{c\,i}$ ($Z_{c\,i}$ = 0 or 1) and there are 23 possible values for TAP_i (TAP_i = –11, –10, … , 0 , … ,11, 10), there will be $(2 \times 23)^{24}$ states in the solution space for our problem. To reduce the computational burden, we first find out the optimal tap position $TAP_{i\ optimal}$ at each stage. This can be done by making $|V_2|$ equals to 1 p.u. and substitute it in Eq.s 10 & 11. Only the three tap positions (the closest to $TAP_{i\ optimal}$, one upper and one lower) are saved at each stage. In this way there are two possible values for $Z_{c\,i}$ and only three possible values for TAP_i and each state node at a given stage will create only six cases at the next stage. To further improve the efficiency of the FDP method, the maximum size of the state space will be strictly limited. To do this, we restrict the number of paths from stage 2 to 24, where after stage 2 there is 216 (36×6) paths which mean 216 solutions, and so on, the number of solutions will grow more & more as shown in Fig. 3. The only 36 paths with the highest objective values among the 216 paths are stored at each state to reduce the final number of solutions which means less execution time for FDP method program.

To obtain a reactive power/voltage dispatching schedule with maximum objective function J, a recursive algorithm has been derived to compute the maximum objective function for state L at stage H (hour H) [11].

$$J(H,L)=\max_{(k)}[J(H-1,K),J_H(H,L)] \qquad \ldots(17)$$

where

$J(H,L)$= maximum total objective function to arrive at state (H,L)

$J_H(H,L)$= objective function for state (H,L)

$$= \mu_{|\Delta \tilde{V}_{2i}|} + \mu_{\tilde{pf}_i} \qquad \text{for } H=1-23$$

$$= \mu_{|\Delta \tilde{V}_{2i}|}+\mu_{\tilde{pf}_i}+\mu_{\tilde{N}tap}+\mu_{\tilde{N}c} \qquad \text{for } H=24$$

(k) =set of feasible states at stage $H-1$

6. The Used Membership Functions

According to the constraints of the FDP method which is mentioned in Eq.s (13−16) the membership functions will be:

6.1 Membership Function for the Fuzzy Variable $|\Delta \tilde{V}_2|$

Since one of our goals is to keep the secondary bus voltage $|V_2|$ near the specified value where the voltage limits are ±5%, a decreasing membership function $\mu_{|\Delta V2|}$ as shown in Fig. 4 is employed.

6.2 Membership Function for the Fuzzy Variable $\underset{\sim}{pf}$

The power factor for a transformer is a good index to determine whether the capacitor should be switched or not. The power factor will be improved after the capacitor is switched, a higher membership value should be given. Based on the experience from the operators at the distribution substation control center, the membership function for power factor is written as in Eq. 19. The membership function is depicted in Fig. 5. In the present work, the same membership function for lagging and leading power factor is adopted :

$$\mu_{\underset{\sim}{pf}} = [1+ (\frac{pf-1}{0.05})^4]^{-1} \quad \ldots(18)$$

where $\underset{\sim}{pf} \geq 0$

6.3 Membership Function for the Fuzzy Variable $\underset{\sim}{N_{tap}}$

Decreasing membership function as shown in Fig. 6 is employed for the total number of switching operations for the ULTC in a day. It is noted that the average number of switching operations in a day for LTC is 7 (according to the experience of the distribution substation control center operators). The maximum number of switching operations that is allowed is 30.

6.4 Membership Function for the Fuzzy Variable $\underset{\sim}{Nc}$

The total number of switching operations for the capacitor, as compared to that for the ULTC is relatively small. According to the practical requirement, the membership function as depicted in Fig. 7 is employed.

5. The Proposed Algorithm

With the same idea of FDP method, but improving the program technique & make changes in its structure, like reducing the comparing process which makes the program execution time much faster. The comparison process needs to make another matrix (with 216 rows and columns equal to which hour the program reached) to save the different values for comparison according to Eq.17.

By ignoring Eq. 17 the comparing operations can be reduced. Ignoring Eq. 17 will make the program takes only the new values of the tap positions without compare it with the values of the last hour, that will maybe affect the number of changing positions for the ULTC in a day (increase them which leads to much consumption for the ULTC) but that is not very important because the number of changings in a day is in the allowable range & the number of changing positions for the ULTC obtained from the new algorithm would not be far from the number of changings obtained from FDP method (the difference would be one or two additional changing movements which is acceptable).

So, getting to the optimum solution for the reactive power/voltage control problem in a distribution substation can be done in no time with the help of recent computers.

First the predicted values would be entered so it is possible to find the six values of tap positions (three when the capacitor is ON and three when the capacitor is OFF) for each hour for the next day. The X matrix is made by distributing the six values of tap for the second hour on the six values of tap for the first hour.

From hour 3 to hour 24 the same procedure is going to be made, the program is going to make a matrix (Y) where the new values of the tap positions are distributed to the rows of matrix X which makes Y matrix consists of 216 rows. After that a comparison is made to save the only 36 rows with the highest values of J in X again (no need to create another matrix). At last, when the hour 24 is reached, the matrix X contains the optimum solution for the reactive power/voltage control problem in a distribution substation in its first row.

The flow chart of the proposed algorithm for reactive power/voltage control problem in a distribution substation is shown in Fig. 8.

6. Case Study

The proposed algorithm is applied on the 132/33 KV Yarmook substation to demonstrate the usefulness of the proposed method. The substation is supplied by two lines (Al-Jazaeer 1 & Al-Jazaeer 2) and delivers power to Al-Jamiaa service area. The substation consists of two transformers, they share the load equally. Furthermore, the rated capacity of each transformer is 63 MVA. The transformer impedance ($\boldsymbol{Z_T}$) is 0.2403 p.u.. The capacitor bank of the substation consists of 30(3×10) MVAr. The method in [12] is adopted to predict the active and reactive power load demands, the primary voltage is forecasted as the average value of the actual bus voltage in the past month. The predicted values for the 21st of June, 2008 are shown in table 1& the load coefficients were assumed as shown in Table 2.

For the purpose of comparison, the resulting reactive power/voltage dispatching schedules at 132/33 KV Yarmook substation for the current method and the new algorithm are summarized in Table 3.

According to the results of Table 3 Fig. 9 illustrates the different between the secondary voltage obtained from the current method at 132/33 KV Yarmook substation and the proposed algorithm.

Fig. 10 illustrates the different between the power factor obtained from the current method at 132/33KV Yarmook substation and the proposed algorithm according to the results of Table 3.

It is very obvious (from fig. 9 & fig. 10) that applying the proposed algorithm gives better voltage profile and much better power factor. Table 4 shows the values of the secondary voltage deviation membership function J_1 and the power factor membership function J_2 at each stage (at each hour) for the Current method at 132/33KV Yarmook substation and the proposed algorithm depending on the results of Table 3. The objective function (Eq.12) and the four terms in the objective function from the final results of Current method at 132/33KV Yarmook subs. & the proposed algorithm are compared in Table 5.

7. Conclusions

This work proposes an algorithm to find an optimum solution for reactive power/voltage control problem in a distribution substation, which means the transformer’s secondary voltage must be kept within the specified range & the power factor must be maintained close to unity. The proposed algorithm achieves that by using fuzzy technique & the coordination between the capacitor with the ULTC, so this algorithm makes a schedule for the ULTC & capacitor status for the next day hours when the forecasted data at hand. In addition, this leads to less dependency on ULTC which leads to less maintenance cost and higher supply reliability. The proposed algorithm also involves the operators constraints, recommendations and also the consideration of variation for load active & reactive power with its voltage, therefore, the results obtained is better than the results of the current strategy. As shown in Fig. 9 the voltage profile improves in some periods of the day, but the significant improvement is in the power factor which is illustrated in Fig. 10. The execution time for the proposed algorithm program is very fast (approximately 1 second) which convertes the program of the reactive power/voltage control from off-line into on-line application.

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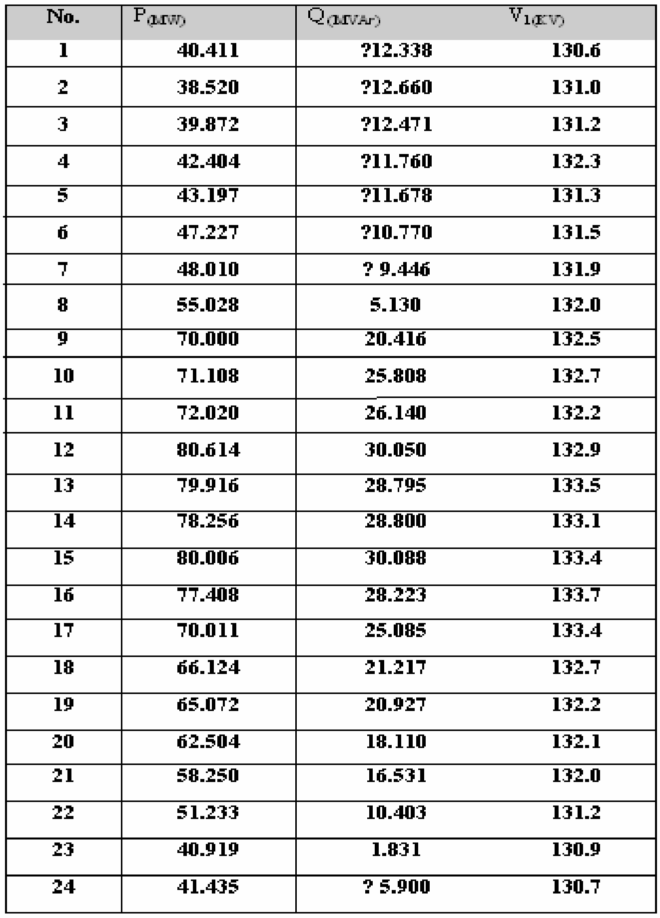
Table 1 The forecasted values for the case study of 132/33 KV Yarmook substation for the 21st of June, 2008 [13].



No.	$P_{(MW)}$	$Q_{(MVAr)}$	$V_{1(KV)}$
1	40.411	?12.338	130.6
2	38.520	?12.660	131.0
3	39.872	?12.471	131.2
4	42.404	?11.760	132.3
5	43.197	?11.678	131.3
6	47.227	?10.770	131.5
7	48.010	? 9.446	131.9
8	55.028	5.130	132.0
9	70.000	20.416	132.5
10	71.108	25.808	132.7
11	72.020	26.140	132.2
12	80.614	30.050	132.9
13	79.916	28.795	133.5
14	78.256	28.800	133.1
15	80.006	30.088	133.4
16	77.408	28.223	133.7
17	70.011	25.085	133.4
18	66.124	21.217	132.7
19	65.072	20.927	132.2
20	62.504	18.110	132.1
21	58.250	16.531	132.0
22	51.233	10.403	131.2
23	40.919	1.831	130.9
24	41.435	? 5.900	130.7

Table 2 The percentage of three different load models for case study.

Coefficient	a	b	c	d	e	f
Magnitude	0.25	0.61	0.14	2.27	−1.72	0.45

Table 3 Reactive power/voltage control dispatching schedules from the Current method at Yarmook substation and the Proposed algorithm.

	TAP		Zc		V_2		power factor	
hour	**C***	**P***	**C**	**P**	**C**	**P**	**C**	**P**
1	−3	−2	0	0	1.0246	1.0262	0.9076	0.9974
2	−3	−2	0	0	1.0232	1.0230	0.9997	1.0000
3	−3	−2	0	0	1.0190	1.0351	0.9935	0.9946
4	−4	−2	0	0	1.0190	1.0333	0.9978	0.9987
5	−4	−2	0	0	1.0212	1.0216	0.9991	0.9997
6	−3	−2	0	0	1.0245	1.0254	0.9087	0.9874
7	−3	−2	0	0	1.0182	1.0312	0.8901	1.0000
8	−4	−2	0	0	1.0310	1.0303	0.9127	0.9820
9	−3	−4	1	1	1.0150	1.0301	0.9088	0.9993
10	−4	−4	1	1	1.0310	1.0295	0.9999	0.9994
11	−4	−4	1	1	1.0183	1.0211	0.9789	0.9810
12	−3	−4	1	1	1.0295	1.0283	0.9976	0.9990
13	−5	−4	1	1	1.0260	1.0238	0.9997	0.9988
14	−5	−4	1	1	1.0160	1.0224	0.8989	0.9969
15	−7	−4	1	1	1.0275	1.0301	0.9798	0.9827
16	−6	−4	1	1	1.0364	1.0349	0.9993	1.0000
17	−6	−5	1	1	1.0308	1.0310	0.9991	0.9999
18	−6	−5	1	1	1.0291	1.0302	0.9935	0.9957
19	−6	−5	1	1	1.0300	1.0307	0.9998	1.0000
20	−7	−2	1	1	1.0121	1.0244	0.9935	0.9913
21	−6	−1	1	1	1.0212	1.0226	0.9757	0.9970
22	−3	−1	1	0	1.0257	1.0264	0.9280	0.9927
23	−2	−1	0	0	1.0298	1.0289	0.9182	0.9949
24	−2	−1	0	0	1.0199	1.0232	0.8945	0.9976

C* : Current method at 132/33 KV Yarmook substation
P* : Proposed algorithm

Table 4 A comparison between the Current method at 132/33 KV Yarmook substation and the Proposed algorithm for J_1 & J_2.

hour	J_1		J_2	
	C	N	C	N
1	0.9538	0.9846	0.0790	1.0000
2	1.8815	1.9077	1.0790	2.0000
3	2.7282	2.7967	2.0787	2.9999
4	3.5749	3.7104	3.0787	3.9999
5	4.4637	4.6066	4.0787	4.9999
6	5.4160	5.5758	4.9012	5.9959
7	6.2483	6.5183	5.5087	6.9599
8	7.1932	7.4731	6.3148	7.9794
9	7.9632	8.4306	7.3148	8.9794
10	8.9076	9.3964	8.3813	9.9794
11	9.7411	10.283	9.3554	10.959
12	10.706	11.265	10.355	11.959
13	11.688	12.204	11.355	12.959
14	12.477	13.115	12.355	13.959
15	13.469	14.073	13.355	14.945
16	14.340	14.964	14.355	15.945
17	15.287	15.910	15.044	16.945
18	16.258	16.866	16.032	17.945
19	17.216	17.815	16.987	18.945
20	17.931	18.765	17.784	19.944
21	18.821	19.681	18.502	20.944
22	19.797	20.669	19.001	21.944
23	20.758	21.643	19.531	22.943
24	21.623	22.570	19.603	23.943

Table 5 Summary of objective function

	J_1	J_2	m_{Ntap}	m_{Nc}	J
Current method	21.623	19.603	0.2088	1.00	42.4348
Proposed algorithm	2.570	23.943	1.0000	1.00	48.513

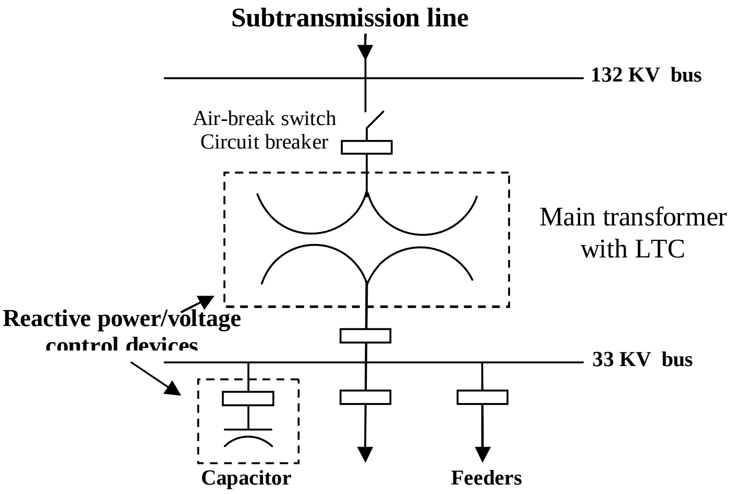


Fig. 1 Part of a 132/33 KV Yarmook distribution substation .

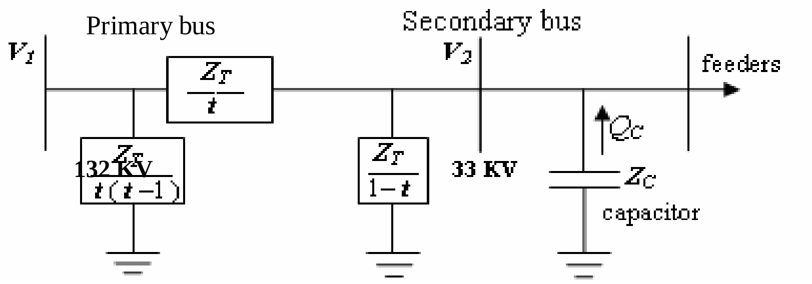


Fig. 2 Mathematical model of a main transformer with ULTC and bus capacitor.

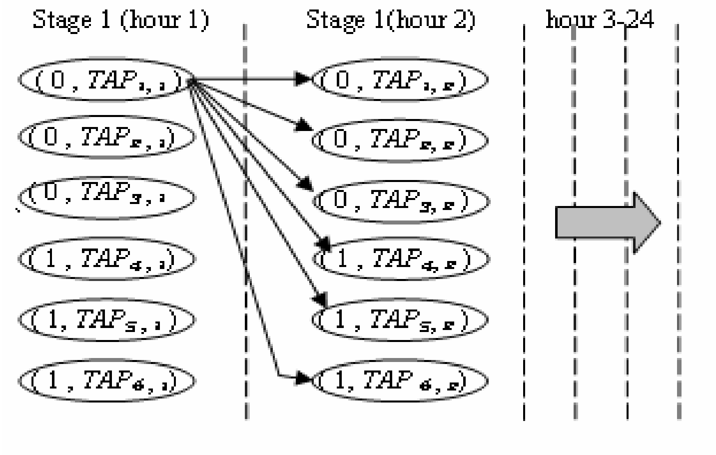


Fig. 3 Illustrates a multi-step problem with 24 steps and each step contains 6 cases (6 states).

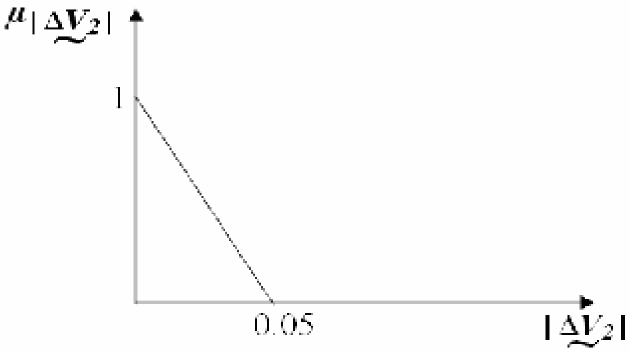


Fig. 4 Membership function for the fuzzy variable $|\Delta \underset{\sim}{V}_2|$

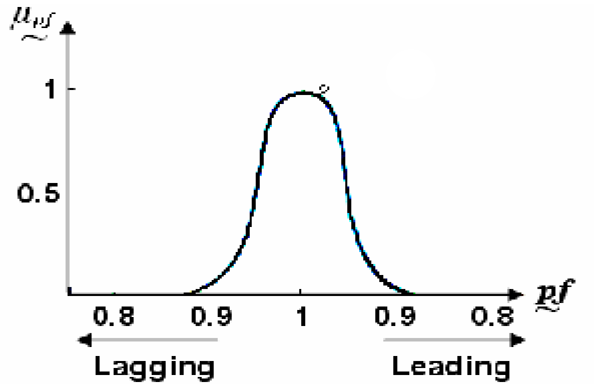


Fig. 5 Membership function for the fuzzy variable $\underset{\sim}{pf}$

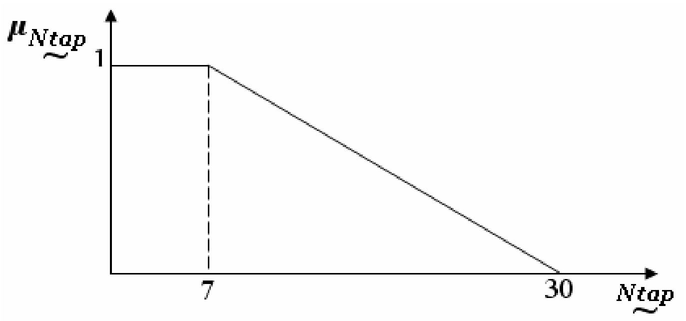


Fig. 6 Membership function for the fuzzy variable $\underset{\sim}{N_{tap}}$

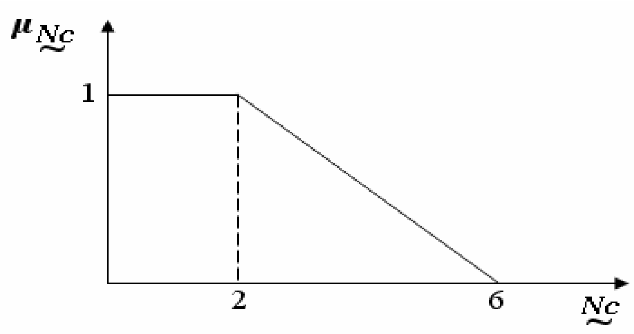


Fig. 7 Membership function for the fuzzy variable $\underset{\sim}{Nc}$

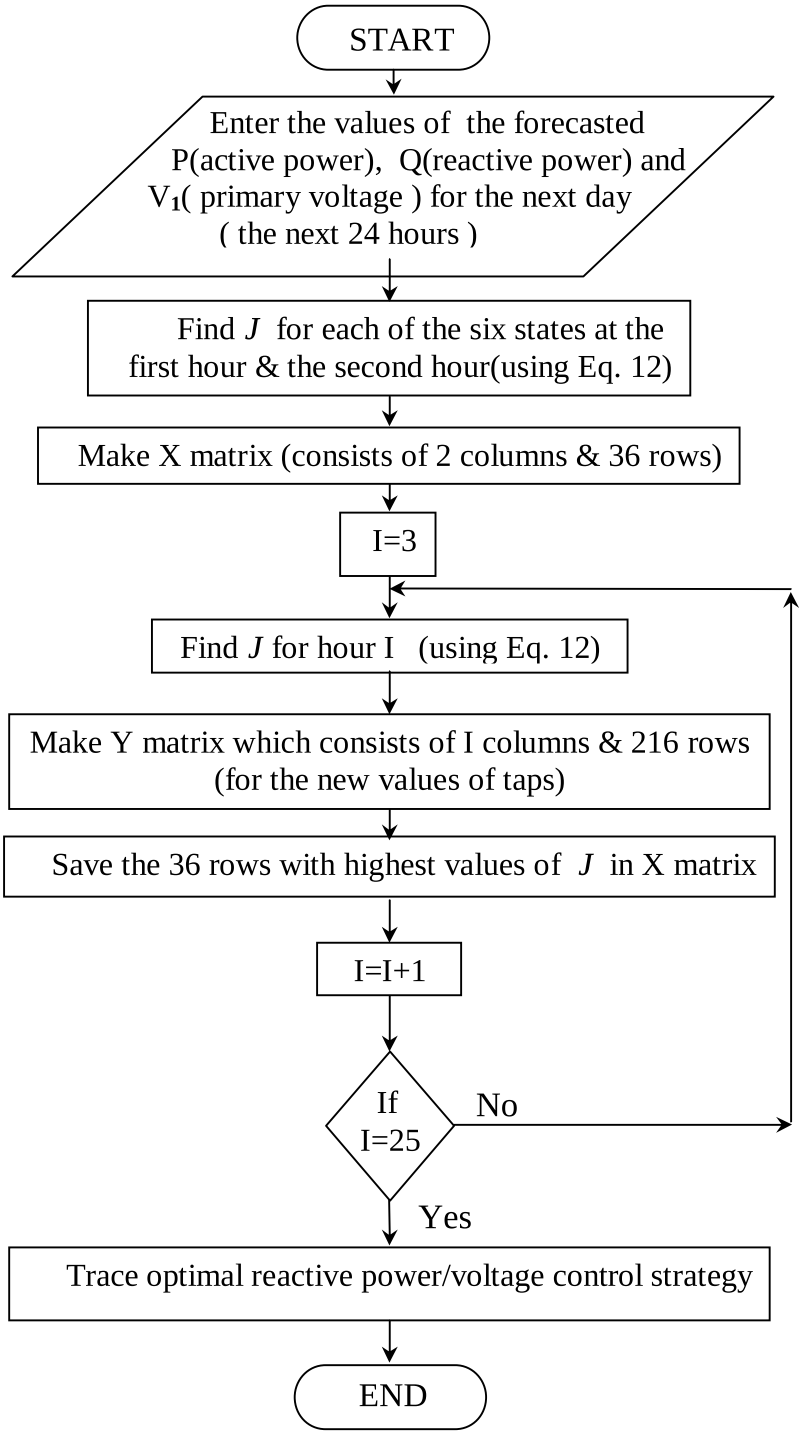


Fig. 8 Flow chart of the proposed algorithm.

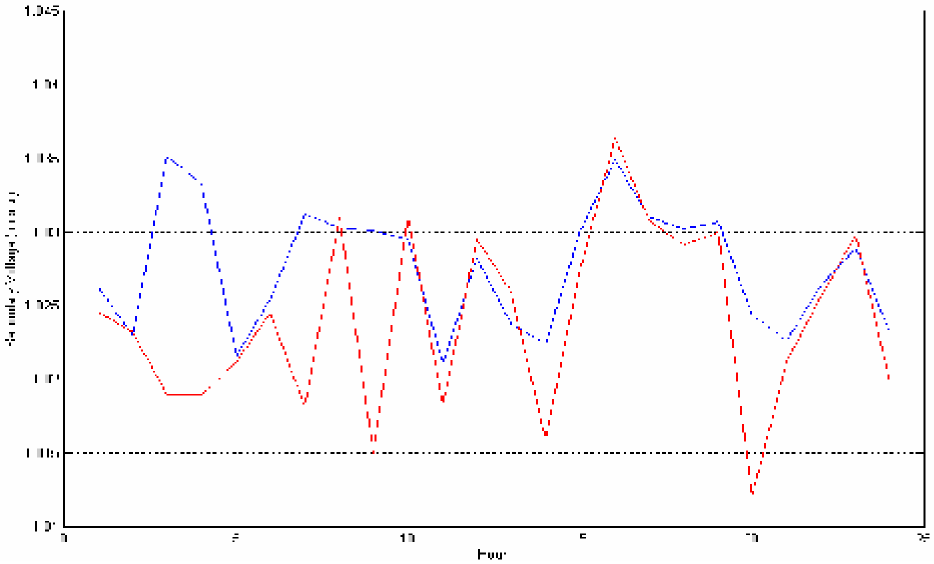


Fig. 9 The secondary voltage obtained from the current method at Yarmook substation in red and the proposed algorithm in blue.

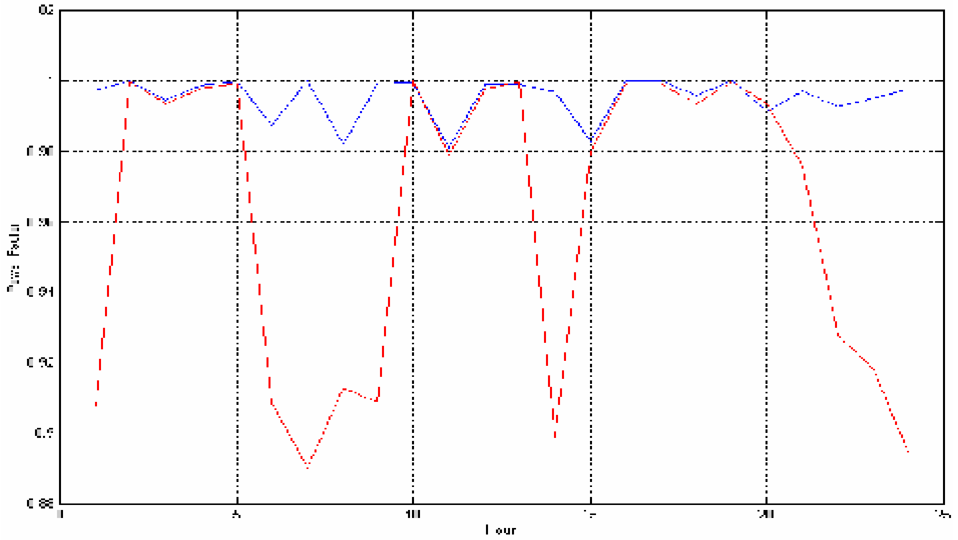


Fig. 10 The power factor obtained from the current method at Yarmook substation in red and the proposed algorithm method in blue.