A New Strategy for Service Restoration and Switching Sequence Determination in Distribution Automation Systems

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Abstract

As DAS becomes a common practice, various operational tools are needed. This paper proposes the new restoration strategy considering the coordination of the protective devices and the generalized method for determining the switching sequence. The effectiveness of the proposed method has been tested on the various real systems.

I. Introduction

The primary feeder system as shown in Fig. 1 has an open loop structure which is operated in a radial fashion. Sectionalizing switches together with protective devices such as overcurrent relays and reclosers are installed to secure the system reliability. Tie-switches are used to give the backup service to the adjacent feeders in case of operational problems such as faults, overload, under/ over-voltage situations.

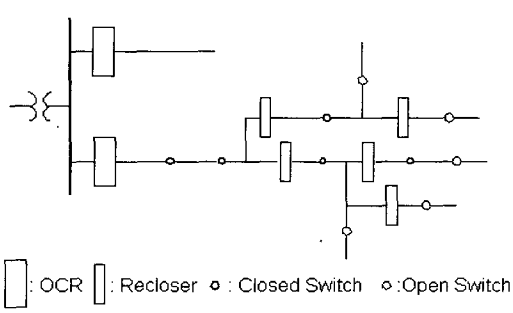

Fig. 1. Primary distribution systems.

As the distribution automation system (DAS) is put intheuristic knowledge in dealing with various operationalo use, various operational tools are needed [1,2,3]. The system problems, whose utilization would enhance the capability of DAS. Therefore the expert system approach has formed the major stream in developing such tools. A typical application of the expert system to diagnose the fault in the medium voltage distribution systems has been reported in [4]. The expert system based service restoration, one of the most important issues in the distribution automation has been introduced in [5,6]. Another application of the expert system can be found in handling the abnormal operating conditions [7].

Authors have been working on the KODAS (Korean Distribution Automation System) project, mainly on the development of the service restoration tool [8,9]. The previous works have dealt with the fully automated system which has only remote-controlled and supervised sectionalizing switches ignoring the protective devices.

However, in automating the distribution systems currently in use, it has been learned that all manual switches can hardly be replaced by supervised switches and the conventional protective devices such as reclosers have still to be utilized. Various tests have revealed that the restoration plan from the developed system could cause misoperation of the protective devices due to the assigned load higher than their settings. Thus those practical factors have suggested the modification of the previous works.

This study proposes the new restoration strategy effective for the system with mixed use of the supervised and manual switches considering the coordination of protective devices as well as the violation resolution strategy in case of the feeder overload and voltage problems. Another important issue addressed in this paper is to determine the switching sequence to make transition from one configuration to another. Execution of the restoration plan or violation resolution plan on the system is made through the on-off manipulation of the

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proper switches. This switching operation should satisfy various constraints imposed by the nature of the problems. From the operators' viewpoint, this switching problem is one of the most important factors since mis-manipulation of switches could cause the crucial damage on the system security. The various operational softwares are being used but each one adopts the different approach to determine the switching sequence utilizing the problem-specific information. Also their resulting switchings are often hard to understand since they usually disregard the geographical locations of switches. Thus the general tool to generate the switching sequence applicable to any problem at hand and easy to understand is strongly needed. In this paper the generalized method for determining the switching sequence which satisfies the above criteria is also proposed.

II. Violation Resolution Strategy

Distribution feeders often experience the overload or under-voltage problems due to the heavy loading. These situations can be resolved by transferring loads of the problem feeder to adjacent feeders. The violation resolution strategy proposed in this study first estimates the amount of the load to be transferred (referred to as 'transfer load' hereafter) in order to remove the violation and then applies the load transfer scheme consisting of five steps - branch transfer, double transfer, level-2 transfer, multi-transfer, load shedding.

The amount of load to be transferred is calculated using the simple formula [9] in case of the voltage problem while the largest one among values defined by Eqs. (1),(2),(3),(4) that denote the overloaded amount on bank, feeder, OCR (Overcurrent Relay), recloser, respectively is selected in case of the overload problem.

$$O_b = \text{bank load} - \text{bank capacity} \quad (1)$$

$$O_f = \text{feeder load} - \text{feeder current limit} \quad (2)$$

$$O_{ocr} = \text{OCR passing current} - \text{OCR setting} / 1.5 \quad (3)$$

$$O_{rec} = \text{recloser passing current} - \text{recloser minimum trip rating} / 1.4 \quad (4)$$

The branch transfer, the first step of the load transfer scheme attempts to transfer the whole branch which has a tie-switch on its end and whose adjacent feeder has a bigger margin than the transfer load. Here settings of protective devices are taken into consideration into the margin calculation in addition to banks and feeders since the load transfer could cause tripping of the protective devices. The double transfer deals with transfer of two branches when no single branch transfer can solve the problem. If the double transfer also fails, the whole outage load is assigned to the backup feeder (referred to as 'level-1 feeder') that has the minimum shortage of the margin and then the its load is transferred to its adjacent feeder (referred to as "level-2 feeder") provided that no overload occur on the level-2 feeder. When no such level-2 feeder exists, combination of the transferable branches whose sum of loads is bigger than the transfer load involving the minimum number of branches is selected. The load shedding for the remaining overload after all possible branches are transferred is finally attempted.

III. Service Restoration Strategy

When a fault on the feeder or bank occurs, the resulting outage area has to be restored as quickly as possible following the fault isolation. Expanding authors' previous works [8,9], the new strategy considering the mixed use of the automatic and manual switches and the coordination of the protective devices has been devised. Realizing that the coordination between the backup and primary devices is valid only for the one direction of the fault current flow, the new scheme transfers the load keeping the same direction and thus minimizing the necessity of resetting the protective devices. Consider the case of Fig. 2 as an example. Note that settings of reclosers R1, R2 and their coordination remain valid if the outage area is restored from the backup feeder BF1. On the other hand, restoration from BF2 would result in the miscoordination. Therefore it would be better not to allow the backup service from the reverse direction of the recloser. This suggested us to make a modification on selection of the appropriate backup feeders of the previous works.

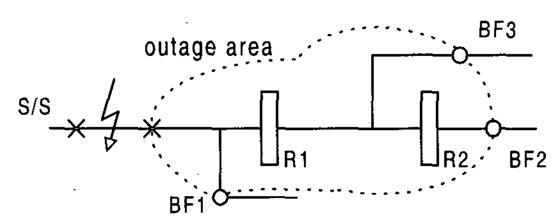

Fig. 2. Directional property of protection coordination.

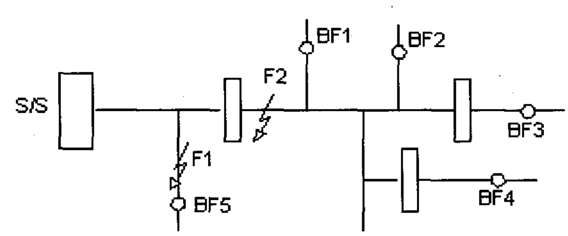

Fig. 3. Distribution systems with reclosers.

Note that there are two types of the outage areas - one containing the no reclosers (fault F1 case) and another containing reclosers (fault F2 case) - as seen in Fig. 3. In the latter case, the previous methodology [9] is applied without any difficulty while in the former case, the newly devised scheme is adopted. Figure 6 shows the flowchart of the proposed scheme where UOA means the outage area surrounded by the open switches and downward reclosers first encountered from the fault isolation switches and LSOA denotes the further downward outage area from those reclosers as seen in Fig.4.

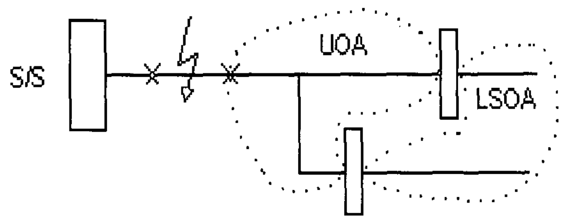

Fig. 4. UOA and LSOA in the outage area.

Identifying UOA, the proposed method first applies Single BF Restoration scheme and if it fails, then depending on the number of BF in UOA, Multi-BF Restoration or Sour-side Outgae Assignment are attempted. When all the outage area are assigned BFs, i.e., the preliminary restoration plan is established, then checking of the operating constraints is performed and if any, its resolution is attempted by making adjustment on the plan. The detailed description of the each scheme follows.

Single BF Restoration: Like the single grouping in the previous scheme, this tries to find one BF that can pick up the whole outage load among BFs surrounding UOA.

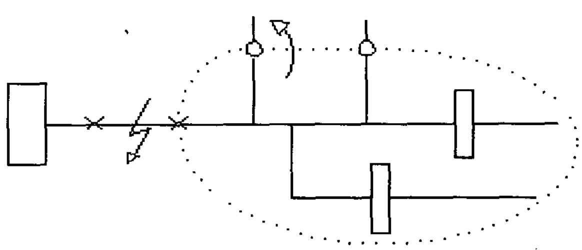

Fig. 5. Restoration by single BF.

Multi BF Restoration: This stage consists of four substeps - recloser branch separation, tie branch separation, second branch separation, one-side separation - whose main idea is to check only certain switches to divide the outage into smaller number of groups instead of testing all possible division points when UOA has more than two BFs. In this study, those switches which are located on the branch points from which the branch extends are to be checked as a separation point candidate.

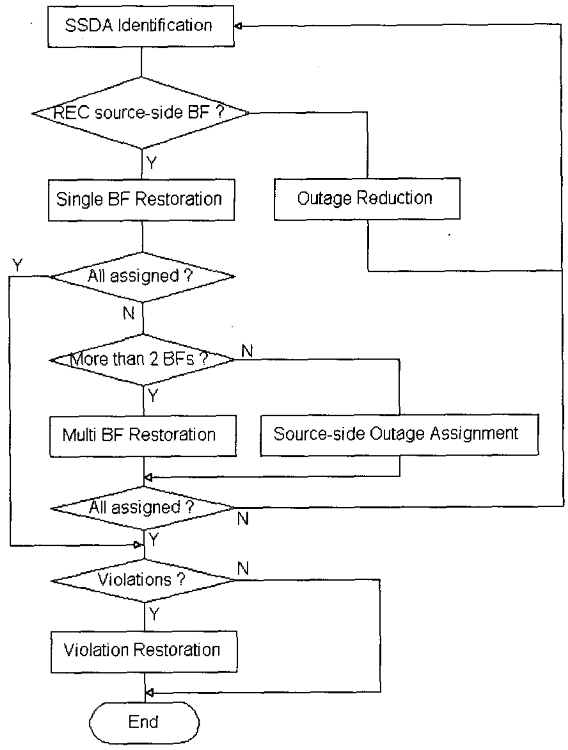

Fig. 6. Restoration procedure for the outage containing reclosers.

i) Recloser Branch Separation: When BFs are distributed at both sides of the recloser branch as shown in Fig.7, two switch positions (r1, r2) from which the recloser branch extends are checked for the outage division based on the loading-distribution-ratio (D_r) defined by Eq. (5)

$$Dr = | 2 * L1 / (L1 + L2) - 1 | \tag{5}$$

where L_1, L_2 represent the outage load to be assigned to each side respectively. Then by dividing the outage area into two at the one with the smaller Dr and assigning the appropriate backup feeder from their side, the restoration is attempted.

ii) Tie Branch Separation: If the recloser branch separation fails, among the branch points (a,b,c,d in Fig.7) from which the branch having a tie-switch on its end (referred to as 'tie-branch') extends, one with the smallest Dr is selected as the separation point for the restoration.

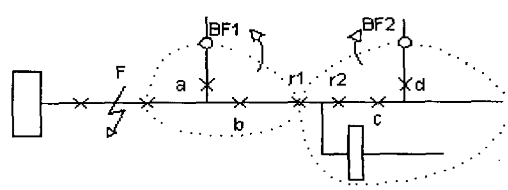

Fig. 7. Area separation at branch points.

iii) Second Branch Separation: If only one side can be assigned an appropriate BF from the previous two steps and the other side without any appropriate BF has more than two BFs, then division of the failed side is attempted at one of its branch separation points (a,b) which has the smallest Dr as shown in Fig.8.

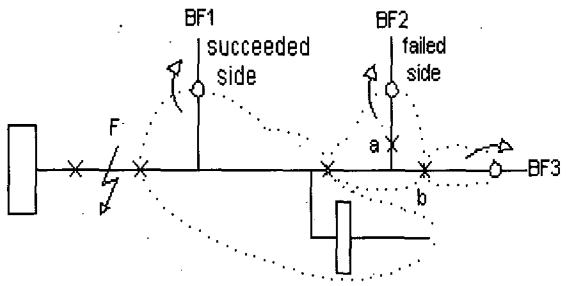

Fig. 8. Separation of the failed side.

<u>iv) One Side Separation:</u> If the separation of one side without an appropriate BF is not feasible, then the following rules are applied for the area division:

R1: if more than two BF's are available then it is divided at the point with the smallest Dr.

R2: if the area has no recloser and only one BF, then the whole area is assigned to that BF.

R3: if the area has any recloser and only one BF, then its UOA is assigned to that BF and the load side beyond the recloser is treated as the target area for restoration initiating the another cycle of the restoration process described so far.

<u>Source-side Outage Assignment</u>: If UOA has only one BF which has not enough margin for the whole outage load, then UOA is assigned to the BF and the remaining outage area, LSOAs are set as the target area for further restoration going through another cycle of the restoration process.

<u>UOA Redefinition</u>: When no BF (backup feeder) is available in UOA, it is impossible to establish the restoration plan which is able to keep the directional property of the protective devices for restoration. In this case, the surrounding reclosers are to be treated as sectionalizing switches and UOA and LSOA are redefined and the process goes back to the starting point.

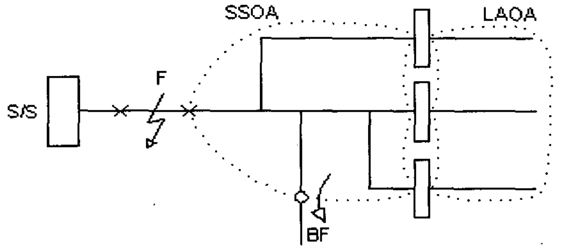

Fig. 9. UOA assignment and LSOA restoration.

IV. Switching Sequencer

Generally speaking, this problem is to determine the switching sequence to make transition from one configuration Gi to another configuration Gf, each of which is specified by the switch status data. This problem can be solved by the logic and the network search instead of the analytic method. There are basically two types of switchings - the restoration switching for the service restoration and violation resolution and the return switching in order to put the system back to the original system or the pre-fault system. Note that these two switchings move the system from the pre-fault configuration to the post-restoration configuration or the other way, they are identical when swapping the input and output data of switch status which specify the system configuration.

There are two important issues involved in the switching problem. One is how to identify each load block which changes its source and its type and the other is to determine the switching sequence among different types, among same types, among close (on) or open (off) switching in each block. This study proposes an efficient method to identify load blocks and to determine the switching sequence, which is described below. The proposed method is explained in terms of the restoration switching problem since the return switching problem is actually same as explained above.

1. Identification of Load Block and Switching Type

Let's consider the situation of Fig. 10 in which the configuration change is indicated by the switch status change. 'on-to-off' or 'off-to-on' in the figure means the change of the switch status from the first status to the second. The system has six load blocks (B0-B5) whose source feeders are to be changed. From the switch status changes, it is not difficult to recognize that they deal with the service restoration. To be more specific, B0, B5 are taken out from the system for the fault isolation and load shedding respectively and B1, B2 which become out-of-service after B0 taken out are transferred from feeder F0 to F1 and F4 respectively for restoration. The live load blocks B3 and B4 are moved from F1 to F2 and from F3 to F1 respectively. Analysing these switchings, we can categorize the switching operations into the five major types whose properties are described in the following.

<u>Load Isolation (LI)</u>: This switching is to open all surrounding closed switches of the specific zone to isolate it from the system and it requires more than one on-to-off switching actions.

<u>Load Shedding (LS)</u>: This switching applied on the feeder end is carried out in order to cut the load from the system and it is same as the load isolation except that it needs just

one on-to-off switching action.

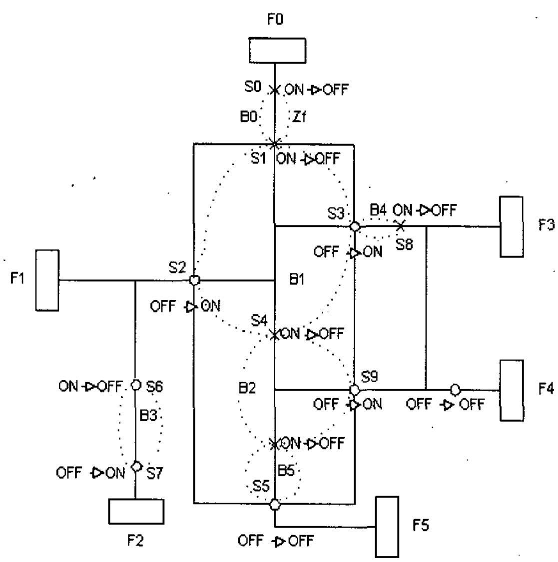

Fig. 10. Switching for configuration change.

Outage Restoration (OR): This represents the switching for the transfer of the outage load to its neighboring live feeder for restoration. It involves some on-to-off switchings to separate it from other loads and one off-to-on switching to supply electricity to the outage area.

Load Transfer 1 (LT_1): This switching is carried out when to transfer the live load from one feeder to its adjacent live feeder and requires a pair of on-to-off and off-to-on switching actions. Note that this pair of switches to be manipulated are located on the direct path connecting two sources.

Load Transfer 2 (LT_2): Among live load transfers, there are sometimes such transfer switchings which have to be made depending on other type of load transfers. For example consider the transfer load blocks B1 and B2 in Fig. 10, which are adjacent to each other. Since B1 would become out of electricity after isolation of B0, if the transfer of B4 precedes the restoration of B1, B4 would experience the outage. Therefore B4 should be made after B1. This could happen when to deal with the fault situation. Similarly in the return switching of the same example, it is desirable that the return of B4 from F1 to F3 be made before the return of B1 from F1 to F0 in order to reduce the possible violation of the operating constraints on F0. Like LT_1 switching, this switching involves a pair of on-to-off and off-to-on switching actions.

2. *Determination of Switching Sequence*

The process to determine the switching sequence is shown in the flowchart of Fig.11. It first identifies all switches which experience the status change and based on these, identifies the load blocks. Then for each load block found, its switching type is identified based on the heuristic rules. The details of the process are described below.

With the problem type and the feeder of concern (Fc) known, the search for the switch with the status change begins from the first switch of Fc and it pushes 'on-to-off' switch first encountered into SW_STACK which has a first-in-last-out data structure. Starting from the switch popped out from SW_STACK, the search proceeds along the feeder trying to find a load block by identifying those load sections surrounded by the switches of any status change. Then the type of the load block is judged by the following rules:

B1: if the load block has only one on-to-off switch and no off-to-on switch on its boundary and only one side has a live source, then it is a LI block.

B2: if the load block has only one off-to-on switch on its boundary, then it is an OR block.

B3: if the load block has no off-to-on switch on its boundary, then it is a LS block.

B4: if the load block has one off-to-on switch and one on-to-off switch on its boundary and both sides have live sources, then it is a LT_1 block.

B5: if the load block has more than two off-to-on switches on its boundary, then it is an OR block with an adjacent LT_2 block.

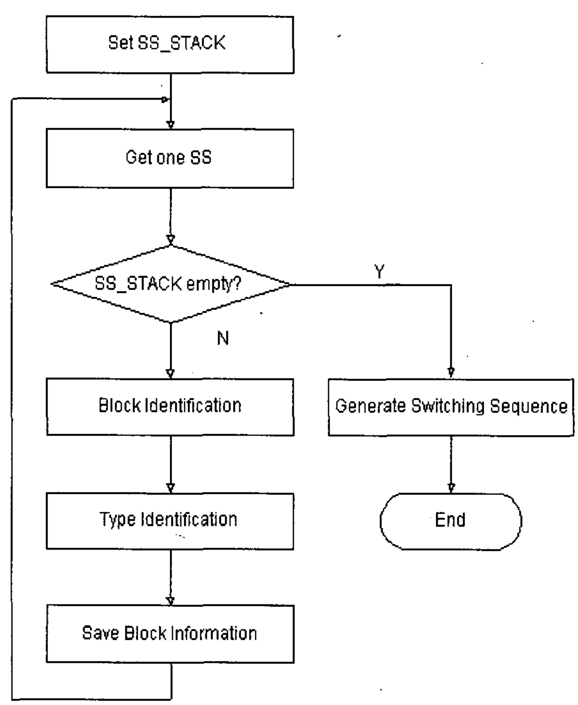

Fig. 11. Flowchart for determination of switching sequence.

When the block is determined as an OR block with LT_2 block, the search for the corresponding LT_2 block is carried out in order to identify the appropriate off-to-on switch. The neighboring feeder connected to the OR block through an off-to-on switch not related to LT_2 could have a LT_1 block to be transferred to other feeder. This situation can be known by searching an on-to-off switch from off-to-on switch and a pair of on-to-off and off-to-on switches for LT_1 can be identified from the direct path to the off-to-on switch from the starting point of the feeder. The load surrounded by these two switches forms LT_1 block. The information on load blocks identified is stored in LB_QUEUE which has a queue structure and also on-to-off switches on the boundary are pushed into the SW_STACK. Note that when an OR block accompanies LT_1 and LT2 blocks, the order to store them in LB_QUEUE is determined depending on the problem type.

The restoration problem puts them into the queue in the order of LT_1,OR,LT_2 and the return problem adopts the order of LT_2, OR, LT_1. The reason for this is to avoid the power interruption of the live load and to reduce the impact on the sound feeder due to the outage load pick-up. After repeating this process until SW_STACK is empty, finally the switching sequence is to be determined utilizing the LB_QUEUE. When many load blocks are involved in the switching, the switching sequence has to be carefully determined in order not to cause any interruption to the live area and to enhance the operators' understandability. For this, the load blocks are searched in a depth-first fashion and saved in LB_QUEUE, and consequently, the final switching sequence is able to reflect the geographical locations of the switches which helps operators to recognize the switchings among the same type of blocks and different types. The way to determine the switching orders among on-off switchings in each block is same as the previous works, i.e., applying the rule of "close-before-open" for the live load transfer and "open-before-close" for the outage load transfer.

In order to help understanding, an example for the Fig.10. The search first identifying S0 as the starting switch, finds a load block B0 which turns out to be a LI block. Another search from S1 identifies B1 block surrounded by S2,S3,S4. With two off-to-on switches, it is known to be a OR block with adjacent LT_2 block according to rule B5. Knowing the existence of LT_2 block, the search continues from S3 which has an on-to-off switch on its direct path to the source F3 finding LT_2 block (B4). Since S6, on-to-off switch can be reached from S2, indicating the existence of LT_1 on the direct path to S7 from F1, a pair of switches (S6,S7) and corresponding LT_1 block, B3 are found. The same process continues starting again from S4 which has been put into the stack, SW_STACK and identifies another block B2 as an OR block. Then one more application of the same process finds LS block of B5. The resulting LB_QUEUE would contain load blocks as seen in Table 1.

Table 1. Contents of LB_QUEUE.

SW Type	Block	on-to-off	off-to-on
LI	B0	S0,S1	-
LT_1	B3	S6	S7
OR	B1	S4	S2
LT_2	B4	S8	S3
OR	B2	S5	S9
LS	B5	-	-

With LB_QUEUE finished, it's an easy job to determine the switching sequence. As the name implies, the way to get the data out from LB_QUEUE is to follow the "first-in, first-out" rule. So the first switching will be the load isolation by opening S0,S1, and the next will be the live load transfer of B3 by closing S7 and opening S6, followed by the outage restoration switching of "open S4, close S2". Then another load transfer of B4 will be performed by "S3 close, S8 open" switching which is necessary to avoid any loading violation due to the transfer of B1. Since two load transfers are relevant to the B1 transfer, their switching commands ought to be presented at this time instead of after finishing all outage restoration switchings. Another outage restoration switching to move B2 will be the next one (open S5, close S9). The last one in Table 1, the load shedding of B5 does not require any switching since the necessary switching has already been done from the previous switchings. Note that by utilizing the queue structure, it has been achieved to generate the switching sequence which reflects the geographical location and the relations between switchings.

V. Conclusions

This paper proposes the new strategy for establishment of the operational plan for the violation resolution to handle the overload and undervoltage problems and service restoration in case of the fault on the feeder. The main features include the search efficiency obtained by focussing on the branch points for the outage area separation and an attempt to preserve the protection capability of the reclosers during the planning. The generalized scheme to determine the switching sequence which is required to execute the established plan is also presented and by conidering the geographical location of the switches, it has achieved the enhancement of the understandability. The system implementing the proposed methodology has been developed in C and tested through various system models showing the satifactory results.

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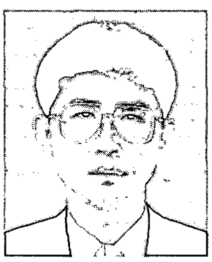

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