مجلة جامعة تشرين للبحوث والدراسات العلمية _ سلسلة العلوم الهندسية المجلد (31) العدد (5) 2009
Tishreen University Journal for Research and Scientific Studies - Engineering Sciences Series Vol. (31) No. (5) 2009

An Expert System for Directional Overcurrent Relays Coordination in Interconnected Networks

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(Received 25 / 11 / 2008. Accepted 7 / 4 / 2009)

□ ABSTRACT □

This paper presents a novel Expert System (ES) for automatic directional inverse overcurrent relays (OCR) coordination in interconnected networks. In the developed ES, the relay setting (determination the pickup current ($\mathbf{I_{PU}}$) and the time dial setting (TDS)) is based on relay setting standards and on the experience of skilled protection engineers.

In this paper, the coordination knowledge is represented in a rule-style (IF – THEN – rule structure), and a forward chaining inference engine is used to carry out the coordination process. The facts and the knowledge base (rules) of the developed ES are represented on a personal computer by making use of an expert system shell, CLIPS (C Language Implementation Production System). The developed ES does not depend on the break points determination in performing the coordination process, but it depends only on the iterative search which is conformed to the built in technique of the inference engine. A numerical load flow and fault analysis programs are integrated within the approach. The developed ES is designed to accept different looped networks configurations.

The developed ES based protection coordination is tested and validated through different case studies using CLIPS. The results showed that the developed ES is reliable and has a high performance, adequate response time, and flexibility.

Keywords: Expert System, Directional Inverse Overcurrent Relays, Relays Setting, Coordination, Interconnected Networks.

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مجلة جامعة تشرين للبحوث والدراسات العلمية _ سلسلة العلوم الهندسية المجلد (31) العدد (5) 2009
Tishreen University Journal for Research and Scientific Studies - Engineering Sciences Series Vol. (31) No. (5) 2009

تنسيق زواجل التيار الزائد الاتجاهية في الشبكات المترابطة باستخدام نظام خبير

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(تاريخ الإيداع 25 / 11 / 2008. قُبِل للنشر في 2009/4/7)

□ ملخّص □

يقدم هذا البحث نظام خبير جديد لأجل التنسيق الآلي لزواجل التيار الزائد الاتجاهية ذات المميزات العكسية في الشبكات المترابطة. يعتمد تعيير الزواجل في النظام المستحدث (تحديد تيار التعيير و مميزة التشغيل الزمني) على المعايير القياسية لتعيير الزاجل و على خبرة مهندسي الحماية الماهرين.

لقد تم في هذا البحث تمثيل الخبرة بالتنسيق بالأسلوب الشرطي (البنية الشرطية – إذا – عندئذ)، وقد استخدمت آلة الاستدلال (الاستقراء و الاستنباط) ذات الاتجاه الأمامي لتنفيذ عملية التنسيق، كما تم تمثيل الحقائق وقاعدة المعرفة (القواعد) للنظام الخبير المستحدث على الحاسوب الشخصي باستخدام بيئة تطوير النظام الخبير المسماة "كليبس" (نظام البناء التنفيذي بلغة سي). إن النظام الخبير المستحدث لا يعتمد على تحديد نقاط القطع في انجاز عملية التنسيق، بل يعتمد فقط على البحث التكراري المتوافق مع التقنية التي تعمل بها آلة الاستدلال. لقد تم إلحاق الطريقة المستحدثة ببرنامجي حساب سريان الحمولة و الأعطال الرقميين، كما أنه تم تصميم النظام الخبير ليقبل أشكال مختلفة من الشبكات المتعددة الحلقات.

لقد تم اختبار النظام الخبير المستحدث لتنسيق الحماية و التحقق منه من خلال دراسة حالات مختلفة باستخدام البيئة "كليبس"، حيث أظهرت النتائج أن الطريقة المستحدثة ذات موثوقية، و تملك أداء عالي، و زمن استجابة ملائم، و مرونة.

الكلمات المفتاحية: نظام خبير – زواجل التيار الزائد الاتجاهية ذات المميزات العكسية – تعيير الزواجل – التنسيق – الشبكات المترابطة.

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Introduction:

Directional inverse OCR, which is simple and economic, is commonly used in power system protection, as a primary protection in a distribution and sub-transmission systems and as a secondary protection in transmission systems. The main problem that arises with this type of relay is the protection coordination. Protection coordination in interconnected networks is tedious and time consuming task for the protection engineers. It involves much repetitious routines dealing with a large volume of data. Moreover, the frequent need to review and readjust the relays setting constitutes an additional trouble to the protection engineers. However, there are several reasons to review the relays setting. For example, when a line is temporarily taken out of service, or after any change in the loading and/or generation conditions. If the relays setting are not adapted in a response to the aforementioned changes, the performance of the protection system would be corrupted [1]. So that, automating the process of protection coordination in interconnected networks would have a great impact on the overall system performance as well as service continuity.

Since 1960s, a great effort has been devoted for developing approaches for automating the protection coordination to assist the protection engineers. Some of these approaches are procedural [2-4], and the others, which are simple, non procedural [5-7]. Ref. [2] introduced a trial and error approach which required a huge number of iterations to be converged (if any). Ref. [3], introduced more systematic approach based on the topological analysis of the network. However, it is required a huge number of matrixes manipulations, and there is no guarantee that the approach will converge. Ref. [4], introduced an optimization based approach for solving the problem of protection coordination, but it still needs the experience of the protection engineers. Ref. [5] adopted an expert system for protective devices setting and miscoordination correction, but the adopted miscoordination corrective method did not guarantee system-wide coordination. Ref. [6] used an expert system shell to implement the Protective Device Coordination Expert System (PDCES) software to correct the miscoordination protective device pairs. Ref. [7], presented an expert system for protective devices coordination based on a break points (the relays by which the coordination process will start) method that required redundant facts and rules; however, the application's results showed that there is no coordination in several cases.

In this paper, a novel six rules based ES is developed for the directional inverse OCR coordination in interconnected networks. The developed ES does not depend on the break points determination in performing the coordination process, but it depends only on the iterative search which is conformed to the built-in technique of the inference engine. The ES is structured using CLIPS shell, which is a forward chaining rule-based language. A computer simulation of the developed ES showed that the ES is reliable and has a high performance, adequate response time, and flexibility.

Importance of the Research and Its Objectives:

The process of directional inverse OCR coordination in interconnected networks involves setting relays one by one, so that at each stage the relay being set should be coordinated with all its primary relays. Therefore, the inherent multi-loop structure of the modern power systems requires a large number of relays setting calculations to be done iteratively around all loops of the system until system wide coordination is obtained. In this respect, a logic approach, based simple IF-THEN-rules, appears to be more suitable for the protection coordination than procedural approaches [2-4] due to the following reasons:

- The coordination process, which is an art more than a science, demands appreciable knowledge and ingenuity of a senior protection engineer.
- Major parts of the relays settings knowledge are available in a rule-style.
- The coordination problem is generally non-procedural and it is solved using heuristics and human expertise.
- Setting of the protection in interconnected systems is basically a search problem in which every primary/backup (P/B) relays pair should be coordinated.
- Expert systems can give explanations about their decisions.

One objective of this paper is to introduce a novel ES, using simple IF-THEN-rules structure that automates the process of directional OCR coordination in interconnected networks, and helps the protection engineer in performing that tedious and time consuming task. Other objective is to introduce a non-procedural coordination approach that is more suitable than procedural approaches that discussed in [2-4].

Methodology and Material:

1- Structure of the Protection Coordination System

An expert system is an intelligent computer program that uses knowledge and inference engine to solve problems that are difficult enough to require significant human expertise for their solution [8].

Figure (1) depicts a block diagram of the developed ES based protection coordination. It consists of two parts: the first one is the ES that works under CLIPS shell, the second one comprises the load flow and fault analysis programs that work under Matlab environment. A brief description of the main components of figure (1) is given bellow:

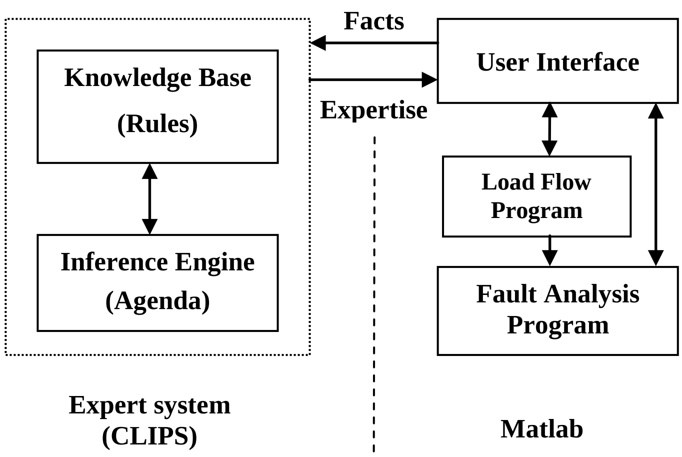

Figure (1) A block diagram for the developed ES based protection coordination.

1. **User Interface:** it is the mechanism by which the user and the ES communicate.

2. Facts: facts are the data on which inferences are derived. Facts are changeable with respect to the network configuration.

3. **Knowledge Base**: it contains all the user defined rules in the form of (IF condition(s) THEN conclusion(s)). These rules are needed to allow proper inferences during the coordination process. Rules are permanent knowledge.

4. Inference Engine: it is the main component in the ES (it is a built-in component in a CLIPS Shell) that process knowledge to draw useful conclusions. It provides methods to control the direction of reasoning (forward and/or backward chaining), as well as strategies like (Depth, Random, Complexity, etc) to guide the search for a solution. It worth mentioning that, forward chaining is reasoning from facts to the conclusions resulting those facts. Whereas, backward chaining involves reasoning in reverse from a hypothesis, a potential conclusion to be proven, to the facts which supports the hypothesis. However, a hypothesis can be viewed as a fact whose truth is in doubt and needs to be established. The hypothesis can then be interpreted as a goal to be proven. In this context, a forward chaining method appears to be more suitable for protection coordination process than a backward chaining method. Moreover, depth search strategy is more suitable for protection coordination process than other strategies because it guides the search in depth for a solution [8].

5. **Agenda**: it is a prioritized list of rules that created by the inference engine, whose rules are satisfied by the facts.

6. **Load flow program:** A Newton-Raphson based load flow program is developed under MATLAB environment to determine the pre-fault bus voltages, line currents at the considered loading conditions, and consequently to determine the relays pickup currents. In this respect, the I_{PU} is determined as1.5 times the line current.

7. **Fault analysis program:** A Thevenin's Equivalent based fault analysis program is developed under MATLAB environment to simulate the faults at required locations, to calculate the P/B relays currents pairs, and to choose the current transformers (CTs) ratios for all relays. In this regard, the CT can be selected according to the maximum load current, but it must not saturate at high level fault currents. According to [9], the secondary current value of the CT must not overreach 20 times the selected CT current rating; otherwise the CT will be saturated.

1-1 The mechanism by which the developed ES work

- The user (protection engineer) triggers the load flow and fault analysis programs, through a user interface, to prepare the required facts to the ES.
- The ES compares these facts with the existing rules, and then the inference engine collects the satisfied rules in the agenda according to their priorities.
- The inference engine then executes the agenda according to the priorities. In so doing, the user obtains the solution of the OCR coordination problem in the form of expertise (the TDS for each relay that satisfies the coordination time interval (CTI) between this relay and its own backup relay(s)).
- If any change occurs in the protected network, operational and/or topological, the user repeats the previous three steps.

In the protection coordination, every primary relay has its own backup relay(s). Therefore, the main job of the developed ES is to find the P/B relays pairs, which are essential for forming the coordination pairs, and to find the TDS for all relays and consequently to calculate the P/B operating times of the relays that satisfy the coordination condition.

In this context, the TDS defines the operating time (T) of the relay for each current value I, overload and/or fault, and is generally given as a curve, T versus M, where, M is the multiple of the $\mathbf{I_{PU}}$ [1]. Hence, M given as follows:

$$M = \frac{I}{I_{PU}} \qquad (1)$$

In this work the OCR is digital and conformed to the following IEC characteristic [10]:

$$T = \frac{k_1.TDS}{[M^{k_2} - 1]} \qquad (2)$$

where, k_1 and k_2 are constants, their values depend on the relay characteristics (normal inverse, very inverse, extremely inverse). It is worth mentioning that the inverse OCR allows for continuous TDS but discrete I_{PU} settings [1, 4].

2 Protection Coordination:

2-1 Protection coordination facts:

As mentioned previously, facts contain data that are generally about a power system configuration (lines, buses) and relays. The templates for the aforementioned facts are as follows:

(**line** <line-ID><bus-from><bus-to>)
(bus <bus-ID>)
(**relay** <relay-ID><bus ><line><CT ratio>< I_{PU}>)
(fault_currents <Primary relay-ID>< fault current><Backup relay-ID>< fault current>)

2-2 Protection coordination rules:

This section introduces a set of general rules to be applied for all relays in the protected system.

<u>Rule1</u> (Forming P/B relays pairs)
IF relay fact is satisfied
AND another relay fact with different ID and line but at other bus of the line of the first relay fact is satisfied
THEN the first relay is back up for a second relay.

<u>Rule2</u> (TDS initiating with a lower bound value (LBV))
IF relay fact is satisfied
THEN the initial value of TDS for this relay = LBV (0.05 according to [10]).

<u>Rule3</u> (calculating the P/B times for this relay)
IF TDS, M $_p$ and M $_b$ are satisfied
THEN calculates the values of POT and BOT for this relay.

where, M_p and M_b refer to primary and backup multiple I_{PU}, respectively, and POT, BOT refer to primary and backup operating time, respectively.

<u>Rule4</u> (checking for the CTI condition between the P/B relays pairs)
IF the time margins (TM) between the P/B relays pairs are less than a predetermined value of the CTI (0.2 in our work)
THEN increment TDS of the backup relay and recalculate POT, BOT.

Rule5 (checking the upper bound value (UBV) for TDS)
IF TDS for any relay is more than the UBV (1.1 according to [10])
THEN print no coordination could be found.

Rule6 (printing the results)
IF coordination process is finished
THEN print TDS, POT, and BOT for all relays.

In this paper, all the abovementioned facts and rules are coded in CLIPS, for example, the code for Rule 1 is given as follows:

```
(defrule backup-primary-relay-pairs
(relay ?r1 ?bus1 ?line1)
(or (line ?line1 ?bus1 ?bus2) (line ? line1 ?bus2 ?bus1))
(relay ?r2 ?bus2 ~?line1)
=>
  (assert (backup ?r1 ?r2)))
```

Results and Discussion:

The developed ES has been applied to two test systems: a 3-bus test system [4], and the IEEE 5-bus test system [11]. In this study, all OCR are assumed to be digital and identical, with normal inverse characteristic, the characteristic constants are: k1 = 0.14, k2 = 0.02 [10], the CTI is taken as 0.2 second. Moreover, the digital relays allow three decimal places for TDS and needless to round of the TDS as it was done in [12].

In implementing the developed ES protection coordination, the $\mathbf{I_{PU}}$ for all relays are calculated in the help of a load flow program, the CTs ratios for all relays are chosen in the help of load flow and fault analysis programs, as illustrated in section (3-1), the P/B relays fault currents pairs are calculated using the fault analysis program. The Facts for each test system are prepared based on the power system configuration. At this phase, all data necessary for executing the developed ES are ready and then the ES executes the coordination process (determines the B/P relays pairs, TDS for each relay and accordingly the P/B relay operating times that satisfy the coordination condition)

1 A 3-Bus Test System

Figure (2) depicts a 3-bus test system. A complete data of this system, as given in [4], is shown below in Table (1). Three-phase faults are carried out at locations F1,…, F6.

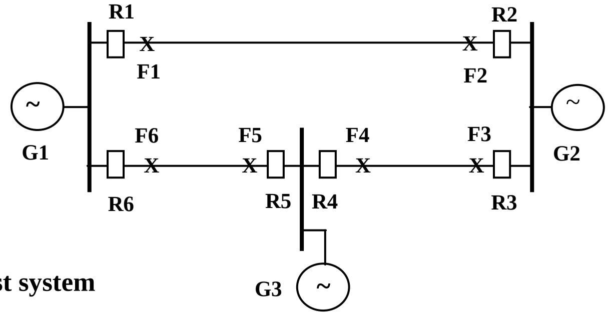

Figure (2) A 3-bus test system

Tables (2-5) depict the results as calculated by the developed ES. Table (2) depicts the fault currents for each B/P relays pair as calculated by the developed fault analysis program. Table (3) depicts the B/P relays pairs. Table (4) depicts the TDS for each relay in conjunction with its own P/B operating times. Table (5) depicts the time margin between each P/B relays pair.

Table (1) A 3-bus test system data as given in [4]

G1	100 MVA	69 KV	20 %			
G2	25 MVA	69 KV	12 %			
G3	50 MVA	69 KV	18 %			
Line 12	50 km	Z = 5.5 + j 22.85 ohm				
Line 23	40 km	Z = 4.4 + j 18.00 ohm				
Line 13	60 km	Z = 7.6 + j 2700 ohm				
Relay Symbol	1	2	3	4	5	6
CT Ratio	300/5	200/5	200/5	300/5	200/5	400/5
I_{PU}	5	1.5	5	4	2	2.5

Table (2) The fault currents for each B/P relays pair in [kA] for a 3–bus test system

BACKUP RELAY SYMBOLE	B_RELAY FAULT CURRENT	PRIMARY RELAY SYMBOLE	P_RELAY FAULT CURRENT
R1	1.1637	R3	2.8956
R2	0.9211	R6	5.0169
R3	1.1309	R5	3.4399
R4	1.2079	R2	2.9398
R5	0.8465	R1	5.0169
R6	0.9942	R4	3.3032

Table (3) The P/B relays pairs for a 3–bus test system

RELAY 1 BACKS UP RELAY 3	RELAY 5 BACKS UP RELAY 1
relay 4 backs up relay 2	relay 2 backs up relay 6
relay 3 backs up relay 5	relay 6 backs up relay 4

Table (4) The TDS and P/B operating times in [Sec.] for each relay in a 3–bus test system

TDS OF RELAY 5 IS 0.152 POT OF RELAY 5 IS 0.272 BOT OF RELAY 5 IS 0.440	TDS OF RELAY 4 IS 0.121 POT OF RELAY 4 IS 0.314 BOT OF RELAY 4 IS 0.515
TDS of relay 1 is 0.099 POT of relay 1 is 0.239 BOT of relay 1 is 0.504	TDS of relay 2 is 0.181 POT of relay 2 is 0.313 BOT of relay 2 is 0.451
TDS of relay 3 is 0.119 POT of relay 3 is 0.303 BOT of relay 3 is 0.472	TDS of relay 6 is 0.120 POT of relay 6 is 0.251 BOT of relay 6 is 0.515

Table (5) The time margin in [Sec.] between each P/B relays pair for a 3–bus test system

TM BETWEEN RELAYS 3 & 5 IS 0.200	TM BETWEEN RELAYS 6 & 4 IS 0.200
TM between relays 5 & 1 is 0.201	TM between relays 4 & 2 is 0.202
TM between relays 1 & 3 is 0.200	TM between relays 2 & 6 is 0.200

2 The IEEE 5-Bus Test System

Figure (3) depicts the IEEE 5-bus test system that consists of 8 lines with 16 relays in conjunction with 40 B/P relays pair. The results of this system, as calculated by the developed ES, are listed in Tables (6-10). Table (6) depicts the currents flow, CTs ratios and I_{PU}. Table (7) depicts the fault currents for each B/P relays pair. Table (8) depicts the B/P relays pairs. Table (9) depicts the TDS for each relay in conjunction with its own P/B operating times. Table (10) depicts the time margin between each P/B relays pair.

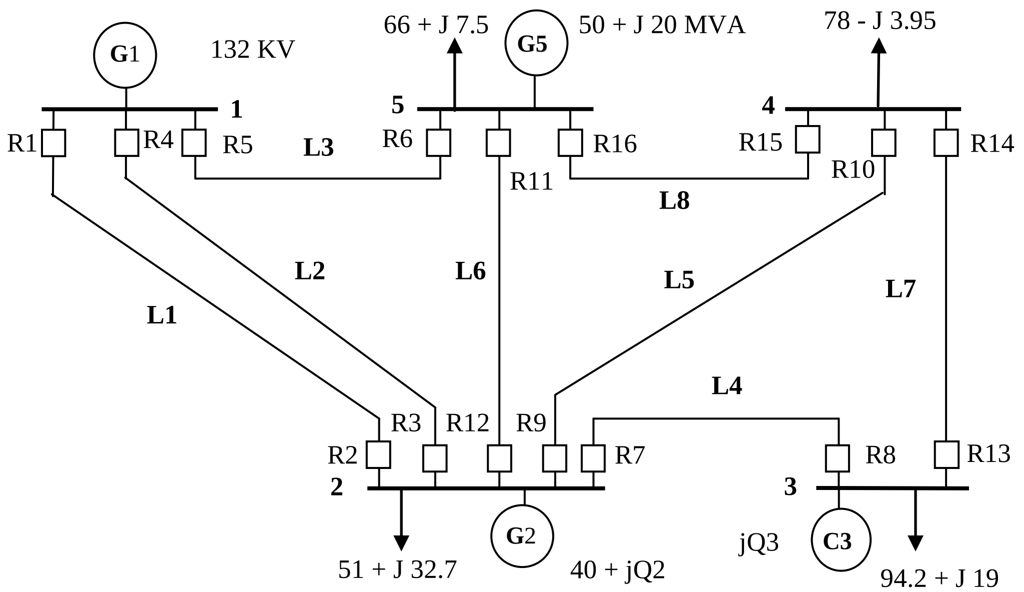

Figure (3) The IEEE 5-bus test system

Table (6) The currents flow, CTs ratios and I_{PU} for each relay in the IEEE 5–bus test system

RELAY SYMBOL	CURRENTS FLOW [A]	C.TS RATIO	I_{PU} (1-12) [A]
R1	307.1165	400 / 5	6
R2	-	200 / 5	1
R3	-	200 / 5	1
R4	307.1165	400 / 5	6
R5	254.3676	300 / 5	7
R6	-	200 / 5	1
R7	275.3653	300 / 5	7
R8	-	100 / 5	1
R9	176.3824	200 / 5	7
R10	-	200 / 5	1
R11	-	200 / 5	1

R12	111.3044	200 / 5	4
R13	-	100 / 5	1
R14	131.6060	200 / 5	5
R15	-	100 / 5	1
R16	289.5297	300 / 5	7

Note: ' - ' means that the current flow is in the reverse direction of the relay operation

Table (7) The fault currents for each B/P relays pair in [kA] for the IEEE 5–bus test system

BACKUP RELAY SYMBOL	B_RELAY FAULT CURRENT	PRIMARY RELAY SYMBOL	P_ RELAY FAULT CURRENT
R1	1.1606	R3	4.4475
R1	1.1606	R7	5.0255
R1	1.1606	R9	4.7765
R1	1.1606	R12	4.5301
R2	1.0237	R4	4.9834
R2	1.0237	R5	5.0344
R3	1.0237	R1	4.9834
R3	1.0237	R5	5.0344
R4	1.1606	R2	4.4475
R4	1.1606	R7	5.0255
R4	1.1606	R9	4.7765
R4	1.1606	R12	4.5301
R5	0.8918	R11	5.4078
R5	0.8918	R16	5.1914
R6	0.9743	R1	4.9834
R6	0.9743	R4	4.9834
R7	1.3140	R13	1.8305
R8	0.6068	R2	4.4475
R8	0.6068	R3	4.4475
R8	0.6068	R9	4.7765
R8	0.6068	R12	4.5301
R9	0.9945	R14	4.1115
R9	0.9945	R15	1.6502
R10	0.7917	R2	4.4475
R10	0.7917	R3	4.4475
R10	0.7917	R7	5.0255
R10	0.7917	R12	4.5301
R11	1.0254	R2	4.4475
R11	1.0254	R3	4.4475
R11	1.0254	R7	5.0255
R11	1.0254	R9	4.7765
R12	0.8104	R6	5.3526
R12	0.8104	R16	5.1914
R13	0.6904	R10	3.8216

R13	0.6904	R15	1.6502
R14	1.3113	R8	1.8266
R15	1.0280	R6	5.3526
R15	1.0280	R11	5.4078
R16	3.1683	R10	3.8216
R16	3.1683	R14	4.1115

Table (8) The P/B relays pairs for IEEE 5–bus IEEE test system

RELAY 1 BACKS UP RELAY 3	RELAY 11 BACKS UP RELAY 3
relay 3 backs up relay 1	relay 11 backs up relay 7
relay 2 backs up relay 4	relay 11 backs up relay 9
relay 4 backs up relay 2	relay 10 backs up relay 12
relay 3 backs up relay 5	relay 8 backs up relay 12
relay 2 backs up relay 5	relay 4 backs up relay 12
relay 6 backs up relay 1	relay 1 backs up relay 12
relay 6 backs up relay 4	relay 12 backs up relay 6
relay 4 backs up relay 7	relay 7 backs up relay 13
relay 1 backs up relay 7	relay 13 backs up relay 10
relay 8 backs up relay 2	relay 9 backs up relay 14
relay 8 backs up relay 3	relay 14 backs up relay 8
relay 8 backs up relay 9	relay 13 backs up relay 15
relay 4 backs up relay 9	relay 9 backs up relay 15
relay 1 backs up relay 9	relay 15 backs up relay 6
relay 10 backs up relay 2	relay 15 backs up relay 11
relay 10 backs up relay 3	relay 12 backs up relay 16
relay 10 backs up relay 7	relay 5 backs up relay 16
relay 5 backs up relay 11	relay 16 backs up relay 10
relay 11 backs up relay 2	relay 16 backs up relay 14

Table (9) The TDS and P/B operating times in [Sec.]
for each relay in IEEE 5–bus test system

TDS OF RELAY 3 IS 0.193 POT OF RELAY 3 IS 0.273 BOT OF RELAY 3 IS 0.403	TDS OF RELAY 9 IS 0.127 POT OF RELAY 9 IS 0.304 BOT OF RELAY 9 IS 0.692
TDS of relay 1 is 0.069 POT of relay 1 is 0.201 BOT of relay 1 is 0.542	TDS of relay 15 is 0.322 POT of relay 15 is 0.488 BOT of relay 15 is 0.549
TDS of relay 2 is 0.193 POT of relay 2 is 0.273 BOT of relay 2 is 0.403	TDS of relay 11 is 0.257 POT of relay 11 is 0.348 BOT of relay 11 is 0.536
TDS of relay 6 is 0.190 POT of relay 6 is 0.258 BOT of relay 6 is 0.403	TDS of relay 7 is 0.122 POT of relay 7 is 0.335 BOT of relay 7 is 0.740
TDS of relay 4 is 0.069 POT of relay 4 is 0.201 BOT of relay 4 is 0.542	TDS of relay 14 is 0.160 POT of relay 14 is 0.359 BOT of relay 14 is 0.584

TDS of relay 5 is 0.071 POT of relay 5 is 0.195 BOT of relay 5 is 0.655	TDS of relay 8 is 0.258 POT of relay 8 is 0.382 BOT of relay 8 is 0.511
TDS of relay 10 is 0.236 POT of relay 10 is 0.346 BOT of relay 10 is 0.537	TDS of relay 12 is 0.153 POT of relay 12 is 0.309 BOT of relay 12 is 0.649
TDS of relay 13 is 0.362 POT of relay 13 is 0.536 BOT of relay 13 is 0.690	TDS of relay 16 is 0.165 POT of relay 16 is 0.447 BOT of relay 16 is 0.560

Table (10) The time margin in [Sec.] between each P/B relays pair in the IEEE 5–bus test system

TM BETWEEN RELAYS 11 & 3 IS 0.263
TM between relays 10 & 3 is 0.263
TM between relays 8 & 3 is 0.237
TM between relays 1 & 3 is 0.268
TM between relays 3 & 5 is 0.208
TM between relays 3 & 1 is 0.201
TM between relays 6 & 1 is 0.201
TM between relays 1 & 12 is 0.232
TM between relays 1 & 7 is 0.206
TM between relays 1 & 9 is 0.237
TM between relays 11 & 2 is 0.263
TM between relays 10 & 2 is 0.263
TM between relays 8 & 2 is 0.237
TM between relays 4 & 2 is 0.268
TM between relays 2 & 5 is 0.208
TM between relays 2 & 4 is 0.201
TM between relays 15 & 6 is 0.291
TM between relays 12 & 6 is 0.391
TM between relays 6 & 4 is 0.201
TM between relays 4 & 12 is 0.232
TM between relays 4 & 7 IS 0.206
TM between relays 4 & 9 is 0.237
TM between relays 5 & 16 is 0.207
TM between relays 5 & 11 is 0.306
TM between relays 16 & 10 is 0.214
TM between relays 13 & 10 is 0.344
TM between relays 10 & 12 is 0.227
TM between relays 10 & 7 is 0.201
TM between relays 7 & 13 is 0.204
TM between relays 13 & 15 is 0.201
TM between relays 11 & 9 is 0.232
TM between relays 8 & 9 is 0.206
TM between relays 9 & 14 is 0.333
TM between relays 9 & 15 is 0.203

TM between relays 15 & 11 is 0.200
TM between relays 11 & 7 is 0.201
TM between relays 16 & 14 is 0.200
TM between relays 14 & 8 is 0.202
TM between relays 8 & 12 is 0.201
TM between relays 12 & 16 is 0.201

It is clear from the results that each relay works as a primary and as a backup relay. Moreover, the developed ES allows three decimal places for TDS and needless to round of the TDS as it was done in [12]. The maximum operating times for the backup and primary relays are equal to 0.515 and 0.314 second, respectively, for a 3-bus test system. Whereas, the maximum operating times for the backup and primary relays are equal to 0.690 and 0.536 second, respectively, for the IEEE 5-bus test system. It is worth mentioning that, it is allowed '1' second time delay for the primary overcorrect relays and 4 seconds time delay for backup relays [3].

The ES execution is carried out on a PC with 1.6 GHz speed. The execution time was 0.2 second for first example and 0.5 second for second example. Hence, the developed ES appears to be more suitable for adaptive coordination of OCR. On other hand, these protection coordination processes may take several hours or days from the protection engineer if he does it manually, irrespective of the mistakes witch may do.

Conclusion and Recommendations:

This paper presented a novel six rules based ES for automatic coordination of directional inverse OCR in interconnected networks. Load flow and fault analysis programs are integrated within the developed ES. The coordination knowledge is represented in a rule-style and a forward chaining method, in conjunction with a depth search strategy, are used in the inference engine to perform the coordination process. The developed ES does not depend on the break points determination in performing the coordination process, but it depends, only, on the iterative search which is a built-in technique of the inference engine. The results of extensive computer simulations of the developed ES, in the help of CLIPS Shell and MATLAB environment, showed that the developed ES has exhibited optimal performance in the studied cases without any miscoordination case.

It is recommended to extend this work to include a new ES system for distance relays setting and coordination, and that is the on-going research to the author.

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