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TRACING INTERFACE DESIGN SOLUTIONS FOR AN ELECTRICITY DISTRIBUTION NETWORK CONTROL SYSTEM USING THE ABSTRACTION HIERARCHY

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Abstract
This paper presents the way we applied the Abstraction Hierarchy method for the redesign of the Control System Man-Machine Interface (MMI) of the Medium Tension Distribution Network of the Public Power Corporation of Greece. A short description of the work domain and the data collection method are first presented. The next section describes the Abstraction Levels that we considered and the sub-domains in which we decomposed the domain. Examples of MMI design requirements derived from the ‘‘stepping’’ across the developed AH space, are then presented, using two representative cases where the operators managed critical events. In the conclusions we discuss the contribution of the adopted method to the redesign of the Man-Machine Interface, respecting the implementation constraints of the domain.

INTRODUCTION

Cognitive Ergonomics is concerned with the design of Man Machine Interfaces (MMI), as a mean that mediates the interaction among humans and other elements of the system, in complex work environments.

Extensive studies have been performed in order to compare different analysis methods and find out the most appropriate for complex work domains (Burns & Vicente 2001, Miller & Vicente 2001). Abstraction Hierarchy (AH) has been proved to have the competitive advantage of representing the work domain through different levels of detail (abstraction), while viewing it from the perspective of different sub-domains provides an effective way to consider all the constraints present in the domain. AH method has been developed by Rasmussen *et al.* (1994) and has already been used in many Control Room design applications (e.g., Itoh, 1990, Jamieson 1998, Reising, 1996).

To accomplish effective interface design solutions, attention must be paid not only to the operators' needs and the work domain constraints imposed to them, but also to the implementation context. The appropriateness of AH to consider the implementation constraints, has already been explored in a nuclear power plant Control Room design project (Burns, 2000).

This paper presents the way we applied the AH for the redesign of the Control System MMI of the Medium Tension Distribution Network (MTDN) of the Public Power Corporation of Greece. A short description of the studied work domain and the data collection method are first presented. The next section describes the Abstraction Levels that we have considered and the sub-domains in which we decomposed the MTDN. Examples of MMI design requirements derived from the ‘‘stepping’’ across the developed AH space, are then presented, using two representative cases where the operators managed critical events. In the conclusions we discuss the contribution of the AH to the redesign of the MMI for the MTDN, respecting the implementation constraints of the domain.

IMPLEMENTING AH IN THE ELECTRICITY DISTRIBUTION MANAGEMENT

The Medium Tension Distribution Network

The Production, Transfer and Distribution Networks can be seen as a unified power system with many interdependent sections, as regards the flow of energy.

Medium Tension Distribution Networks (MTDN-20kV) are spread around the big cities, conveying energy to the final customers. The MTDN-20kV of the city of Athens Greece is partitioned in three areas of authority, which are managed by three Control Rooms, autonomous regarding the operations but interdependent regarding energy flow.

The MTDN-20kV is remotely monitored but only partially remotely operated. The remote monitoring covers all the protection functions and status changes of the lines' oil-switches in the Distribution Centers, as well as “passing fault recognition” and switches' status change of the Remote Operated Substations. Remote operation (open/close actions) is provided only for the lines' oil-switches of the Distribution Centers and of the Remote Operated Substations. The remaining operations are carried out in situ by Foremen crews. The Foremen work always under the instructions of the dispatchers who work in the Control Rooms; they search and transfer information about the network state and execute actions on network equipment. Consequently, the role of the Foremen crews is crucial for the network management.

Data Collection and Analysis

The required data for the analysis were collected through systematic observations of the personnel's actions in the MTDN Control Room, during a six months period and both at normal and degraded situations. Directed interviews with dispatchers, engineers and other experts contributed a lot in understanding the structure, the functions and the capabilities of the existing technological equipment and engineering applications.

The Abstraction Hierarchy space of the MTDN

The Abstraction Hierarchy (AH) unfolds through a two dimensional representation and offers the required flexibility for describing each work domain in different terms and degree of detail through the hierarchical levels (vertical dimension) (Rasmussen, 1994). AH provides also the possibility of viewing simultaneously the same system from different domain points of view (horizontal dimension). Having in mind the goal of our analysis (redesign of the MMI) and the technical constraints of the MTDN, we decomposed the MTDN into the following sub-domains:

Network - Technological Equipment: comprises all the components (transformers, cables, circuit breakers, knife switches, switch boards etc.) which participate in the distribution of energy from the high/medium tension substations to the medium/low tension substations.

Control System - Technological Equipment: includes all the technological means for the timely transfer of information (measurements, activated alarms) or transmission of commands and status changes from/to the technological network.

Control System - MMI: consists of the mimic diagram, the control panel, the operators' desk, as well as the handwritten and electronic records.

Foremen Crews: as already noted, they can be considered as the extension of the control system, as they monitor and operate the equipment which cannot be managed remotely.

We considered the following abstraction levels:

Functional Purpose (FuPu): The generic purposes of each sub-domain and the constraints of its coupling to other sub-domains and the environment are described at this level (e.g., the Network - Technological Equipment must supply energy and work properly even when the environmental temperature exceeds 39°C, the Control System - Technological Equipment should transfer uninterruptedly commands and status changes from/to the network, while the Control System - MMI should represent properly all this transferred information). Policies and strategies are also described at this level (e.g., the management policy of the Network - Technological Equipment is to supply continuously the requested quality and quantity of energy.

Abstract Function (AbFu): The topics at this level are (i) setting priorities (e.g., a distribution line of the Network which supplies energy to a hospital, has priority in restoration management scenarios), (ii) allocating energy flow (e.g., when a high voltage line of the Network is overloaded, the medium tension transformers have to decrease their loads), and (iii) information flow between sub-domains.

General Function (GeFu): This level describes the general functions that each sub-domain is intended to carry out (e.g., the Control System - Technological Equipment transfers data about the status of oil-switches, while the Control System - MMI represents the load of distribution lines).

Physical Function (PhFu): This level describes (i) the physical processes and behavior of the equipment and tools (e.g., network's line overload protection provided by the Control System - Technological Equipment), (ii) their characteristics under different conditions of use (e.g., the transformer's permissible load limit is lower than usual under extreme heat environmental temperatures), and (iii) the available means to control system performance (e.g., the remote operated substations have a 'passing fault detection' application, which aids significantly the fault management task).

Physical Form (PhFo): This level represents the specific characteristics, the form and the location of each sub-domain's equipment and means (e.g., the technological generation of a Network's transformer, the topological proximity of two substations of the Network, the value of a line's load presented at a display of the MMI).

A similar AH space has been developed for the High Tension Network of 150kV in order to analyze the cases requiring cooperation between High and Medium Tension Control Rooms.

“STEPPING” ACROSS THE AH SPACE

AH spaces were used to model the operators’ cognitive processes for the management of different critical events. The trajectories (S1 |S2 |S3 |…Si) followed by the MTDN Control Room operators during the management of two representative cases are presented here. Each step (Si) was determined by the specific constraints and information considered by the operators managing the critical events.

case 1	**150 kV Network Tech..Eq.**	**150 kV Control System Tech.Eq. &MMI**	**20 kV Network Tech. Eq.**	**20 kV Control System Tech.Eq. &MMI**
FuPu	S-7		S-9	
AbFu	S-8 S-6		S-10 S-19 S-11	
GeFu		S-1 S-3 S-12		S-14
PhFu	S-2 S-13	S-4	S-16 S-18	S-15
PhFo	S-20 S-5		S-17	

Figure 1: ‘‘Stepping’’ across AH space for Case1

The first case (Figure 1) refers to the actions carried out by the operators of the MTDN-20kV Control Room, to manage a modification in the High Tension Network-150 kV. The main concern of the operators is to check if the consumers who are supplied from a specific 150 kV line, could be supported from alternative ways of the MTDN-20kV. This case has been mainly driven by two constraints: the continuous supply of power to the customers (S-7, S-9 / FuPu) and the balance that must be always kept between the energy transferred by the 150 kV lines and the energy that is distributed through the MTDN-20kV (S-6, S-8, S-10, S-11, S-19 / AbFu).

The fact that each Control Room has access to different representations (S-5 and S-17 / PhFo) and functional constraints (S-13 and S-18 / PhFu) of the network, generates the need for communication between the 20kV and 150 kV Control Rooms (S-12, S-14 / GeFu).

Based on the analysis of the above case, the following requirements for the new MMI design were formulated: (i) visual access to all the involved network’s topological representations, at both Control Rooms, should be provided, (ii) constraints related to equipment’s load limits should be presented, (iii) the relation between parameters which are interconnected (energy flows) or propagation of effects (increase in energy consumption) should be also properly presented.

case 2	**150 kV Network Tech..Eq.**	**150 kV Control System Tech.Eq.&MMI**	**20 kV Network Tech. Eq.**	**20 kV Control System Tech.Eq.**	**20 kV Control System MMI**
FuPu					
AbFu	S-4		S-5		
GeFu		S-10 S-11 S-13			S-1 S-7 S-9 S-14 S-15.1 S-15.2 S-17 S-19
PhFu	S-12		S-3.1 S-3.2		
PhFo			S-16 S-18	S-6	

Figure 2: ‘‘Stepping’’ across AH space for Case2

The second case (Figure 2) represents the operations which follow the activation of the ‘‘load rejection function’’ in a specific Distribution Center (S-12 / PhFu). The operators should check if real (low frequency problems in the network) or fictitious (relay’s malfunction) symptom has occurred (S-5 / AbFu, S-6 / PhFo). To diagnose this problem, they checked the oil-switch status of other 20 kV Distribution Centers (S-8 / PhFo) and crosschecked their findings with information from the 150 kV network (S-10, S-11 / GeFu and S-12 / PhFu). To gain information about the relay’s condition in the Distribution Center, they asked a report from an engineer in charge (S-15.1 / GeFu).

Based on the analysis of the above case, the following requirements for the new MMI design were formulated: (i) appropriate information to easily discern if a symptom is caused by the network’s disturbance or by the control system's equipment malfunction, should be provided, (ii) the access to other Control Room's representations and functions (e.g., eventual activation of 'load rejection function' from the 150 kV Control Room) should be obtained, (iii) system's safety critical information should be supplied (e.g., information about the relay's functional state).

CONCLUSIONS

The requirements for the design of the new Man-Machine Interface of the MTDN have been derived form the analysis of 30 representative management cases, covering critical usual and unusual events.

The AH spaces we adopted:

- highlight the role, the available means, the functions and goals of each sub-domain,
- determine the limits of each sub-domain's authority.

The analysis of the operators' cognitive processes during the management of critical events using the AH spaces, permitted the identification of:

- the origins of the constraints imposed to the operators,
- the constraints leading to the adoption of specific strategies by the operators,
- the constraints inducing specific actions of the operators,
- the specific information needs at each step of the cognitive processes,
- the propagation of constraints across the different sub-domains.

The adoption of every design requirement for the Man-Machine Interface of the Control Room, is strongly dependent from the availability of specific means and functions in the other sub-domains (i.e. the Network- and Control Room- Technological Equipment). The way that we decomposed the MTDN domain, permitted to consider the propagation of constraints between the different sub-domains as well as their effects to sub-domains' capabilities. Consequently, the proposed design requirements not only alleviate the operators work, but also respect the implementation constraints.

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