THE PREDICTION OF LOAD IN PROCESS OF RESTORATION OF POWER SUPPLY IN A DISTRIBUTION SYSTEM

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1. INTRODUCTION

Due to its large number of elements and their nonlinear relations, the distribution system is subject to frequent disturbances and faults, which can lead to a partial or complete blackout. Disturbances have transient character and could therefore be eleminated by autoreclosure, whereas faults require a longer clearance time. The remedial actions after a fault include changing of the distribution system structure by switching and reconfiguring the network.

When a fault occurs in such a network, some of the load may be restored through switching and reconfiguring the network. Sometimes switching is not possible, so the fault must be cleared before the consumers can be reconnected to the network.

If the outage takes more than one hour, the immediate reconnection of all the consumers may not be sustained. Immediately after energizing the feeder, high currents may arise which could exceed the steady state values by two to five times. This phenomenon is called Cold Load Pickup (CLPU) and is a consequence of loss of load diversity.

In steady state, the load is always diverse because all devices are never switched on at the same time. After an extended outage, devices connected to the network will start as soon as the power is restored and load diversity will be lost. The longer the outage, the greater are the loss of load diversity and the resulting initial currents at reconnection of the loads. Theoretically, if all the loads would be switched on at that time the loss of load diversity would be complete. Due to diverse load characteristics, this situation occurs only in extreme cases.

A very important factor in restoration process is the way in which the load is controlled. The loads can be controlled manually or automatically. During CLPU, the influence of automatically controlled loads, especially thermostatically controlled loads, is prevalent.

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2. INDIVIDUAL LOAD OBJECTS

The consumers were divided into three main groups, i.e. residential, industrial and commercial. For industrial load will be considerably lower as compared to normal operation. It will take hours (in exstreme cases as sensitive processing industries up to days) before a normal power consumption is achieved.
For the residential sector, however, the power demand after an interruption may be considerably higher as compared with the pre-outage situation.
Because, in this paper the residential load is analysed.
Thermostatically controlled loads such as refrigerators, freezers and air conditioners are,like different types of lighting,common load objects in the power system.Their behaviour after a disturbance is therefore of interest.

2.1 Refrigerators and frezers

The aggregated power consumption for six refrigerators and freezers after a 3 hours outage, which is shown in fig.1, is modelled according to (1) :

$$\mathbf{P=P_0(1+Ae^{(-t/Ta)})} \qquad \mathbf{(1)}$$

where P_o is the mean power consumption during normal operation. *A* and *Ta* are constants which vary with different refrigerators and freezers but also with the duration of the outage. Following a 3 hours disturbance *A* is 2,3 pu and *Ta* is about 0,7 hours for the six refrigerators and freezers investigated.

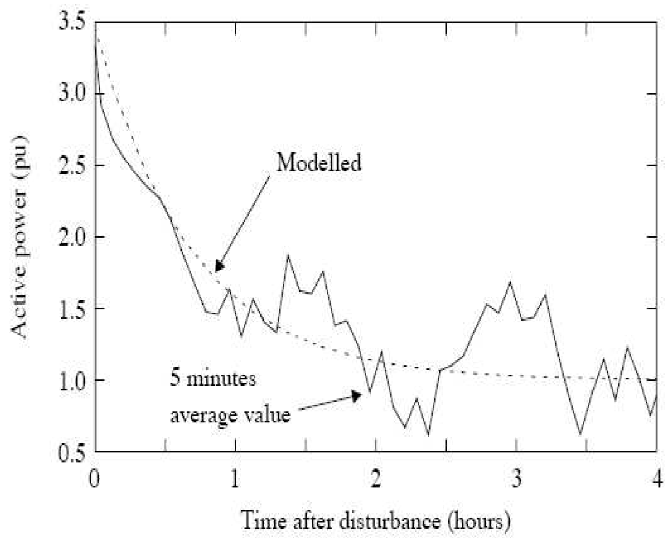

Figure 1: Active power consumption for the aggregation of 6 refrigerators and freezers after a 3 hours outage. Base power is stationary power.

2.2 Air conditioners

Air conditioners (AC's) are working in the same way as refrigerators and freezers. Fig 2 shows a measurement of an air conditioner following a disturbance. As can be seen it takes some minutes before the pesk in power is achieved and this is in contrast with refrigerators and freezers where the peak occurs immediately. It is also noticeable that the peak value of the power consumption is lower for AC's as compared with refrigerators and freezers.

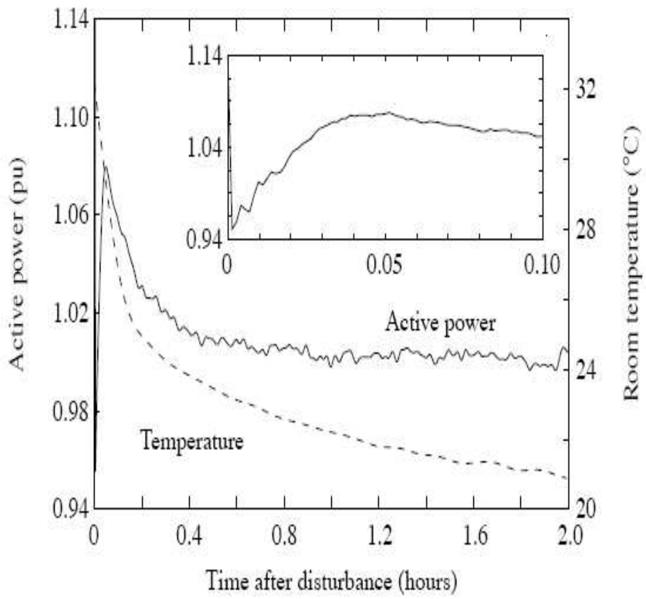

Figure 2 : Active power consumption and room temperature after a disturbance of an air conditioner. Base power is stationary power.

2.3. Electric heating

Electric heating is mostly based on electric boilers,electric radiators and (to some extent) different types of heat pumps.

Electric boilers are used for heating the tap water and for the heating up of water which is transported in pipes to radiators heating up the air in the rooms.

Heating based on electric radiators is more direct way of heating up a house.

Heat pumps use the heat from the outside air or the water from a lake,water from a deep hole in a mountain or from the soil. It is also common that a small heat pump uses the exhaust air from a house. For district heating purposes large heat pumps which use waste heat from industries or waste water are common.

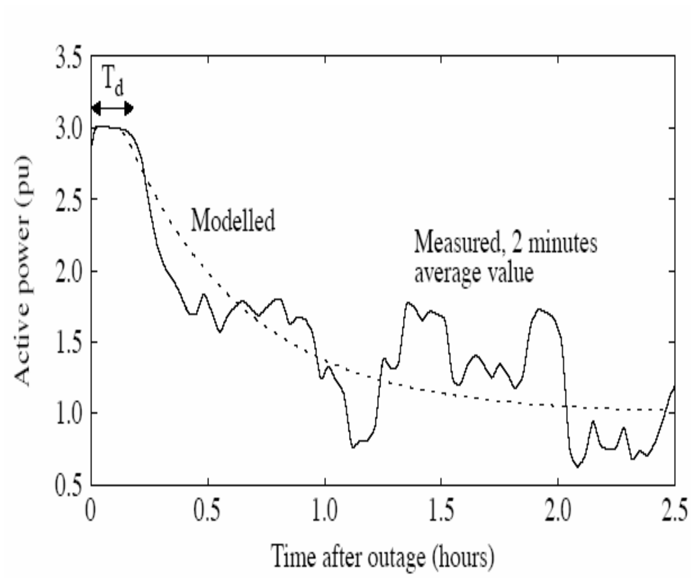

Figure 3: Aggregation of electric heating after a four hours outage. Outside temperature about 0 °C. Base power is stationary power consumption

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In fig. 3 an example of the modeling is shown for a 4 hours outage with an outside temperature of about 0 °C.The aggregated electric heating is modeled according to (2):

$$P=P_0(1+Ae^{(-(t-Td)/Ta)}) \quad , \quad t>Td \qquad (2)$$

where Po is the stationary power consumption, Td the delay time, Ta a time constant and A a constant. The model is valid for t>Td; for t<Td the power consumption is P=Po(1+A).
The load peak is strongly related to the outdoor temperature and the duration of the outage.

2.4. Lighting

Incandescent lamps are widely used as lighting sources. However, the low luminous efficiency and the relatively short life of incandescent lamps have made several types of discharge lamps very popular in different applications . Fluorescent lamps are common as interior lighting in households, offices, supermarkets, industrial plants and in public buildings. Mercury lamps are used in warehouses and industries. Together with high pressure sodium lamps they also often illuminate streets in cities and hosing areas whereas low pressure sodium lamps mostly are used for illuminating motirways.
When street lighting is switched on it takes some minutes before a proper light quality is achieved. In the lamps the pressure and the temperature will increase during this start up period. As can be seen in fig. 4 the power consumption of these lamps will also be lower in the beginning and reaches a stationary level after some minutes. In contrast the power consumption for low pressure sodium lamps reaches its stationary level almost immediately. For fluorescent lamps more than 90% of the power consumption is reached almost instantaneously wen the lamps are switched on. The remaining part takes some minutes and is related to the increase of the temperature and pressure in the tube.
For an incandescent lamp the power consumption will be high for some periods and then reach a lower stationary level when the filament in the lamp is warmed up.

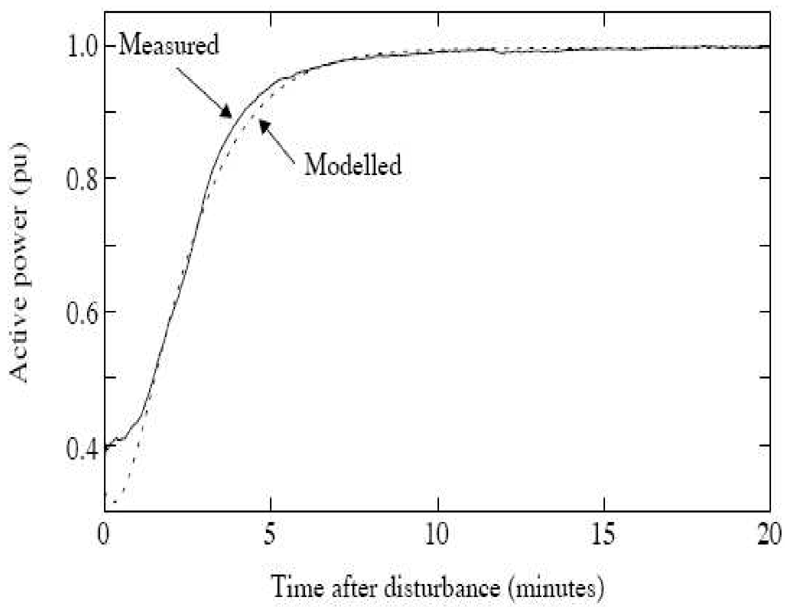

Figure 4: Active power consumption for a high pressure sodium lamp (250W) during the start up phase. Base power is stationary power

2.5. Other household equipment

In a household there are many different types of equipment consuming electric energy. For some type of equipment the psychological behavior of people will affect the power consumption after a disturbance

substantially. For example if people are preparing food in the oven they will probably stop the process, especially if the duration of the disturbance is long. However, if people do not react (which is likely if the duration of the outage is short) the temperature in the ovens will have decreased during the4 disturbance and since theory are thermostatically controlled they will all be in the on state when the voltage supply comes back. The fact that people have not cooked during the disturbance and are getting hungry must also be taken into consideration since they will probably start to cook when power is restored.
Washing, drying and dishing machines will probably not be switched off to the same extent as stoves and ovens and instead people will let the laundry and dish stay in the machines. There are two types of washing and drying machines. One type of machine has to be manually restarted after a disturbance anther type continues it's programmed. For large washing machines, which mostly are used in wash-houses in block of flats, it is common that in cases of loss of voltage the machines will be drained of water and they therefore have to be refilled with water when restarted. As a consequence the active power consumption will be on its highest level after a disturbance since the water has to be heated up.
Radios and television sets will probably not be switched of by people during a disturbance. Some television sets will after a disturbance enter the stand-by position and switching over to the on state has to be done manually. Computers restart or enter a stand. by position after an outage.

3. LOAD MODELING

An impoortant data for network restoration is load behavior. Every low voltage (LV) 10 (20)/0,4 kV Substation has its own daily load characteristic that depends on load structure. Load characteristics can only be determined precisely by measurements.
For the purpose of modeling load behavior, numerous measurements were carried out.

3.1. Steady state load determination

Steady state load can be determined through current flowing in normal conditions. Hourly values of the total current of each feeder and each transformer are presented in a daily load diagram, which differs by days of the week as well as by seasons. The currents are measured monthly on a third Wednesday at middle voltage (MV) 20 kV substation transformers and feeders. Currents in LV substations are in general not available and can be estimated from the MV feeder currents by:

- load estimation based on load distribution with regards to rating power of LV substation transformers.
- statistical estimation or by an approach based on fuzzy set theory, and
- estimation of load based on operatior's experience.

The first method is based on a fact that the load is distributed proportionally to the rating power of the LV substation transformers. From the available feeder current I_{FD}, the current of the LV substation j, I_j, is derived as :

$$Ij=I_{FD}(Si/\Sigma Si)\ ,\ i=1....N \qquad (3)$$

where S_i is rated power of LV transformer at i-th substation and N is a number of LV substations that are supplied from the feeder.

3.2. Cold load pickup model

In normal operation, load diversity depends on the nature of loads and consumers lifestyle. Thermostatically controlled loads have a major impact on load diversity. For example, duty cycle of a refrigerator lasts 15 minutes and its non-duty cycle 30 minutes. Since during normal operation not all refrigerators are the duty cycle at the same time, load can be deemed diverse. The behavior of other thermostatically controlled devices is very similar to that of refrigerators. After an extended autage, all

thermostatically controlled devices will start as soon as the power is restored and load diversity will be lost completely.
The consumers on the other hand control manually controlled loads. An accurate prediction of the characteristic od these foads during CLPU is very difficult because is largely influenced by the lifestyle od the consumers. In general, a higher amount of manually controlled loads can be expected immediately after restoration because many consumers may want to complete their unfinished tasks as soon as possible after restoration of power, again reducing load diversity.
The model in Fig. 5 shows load behavior during restoration process.

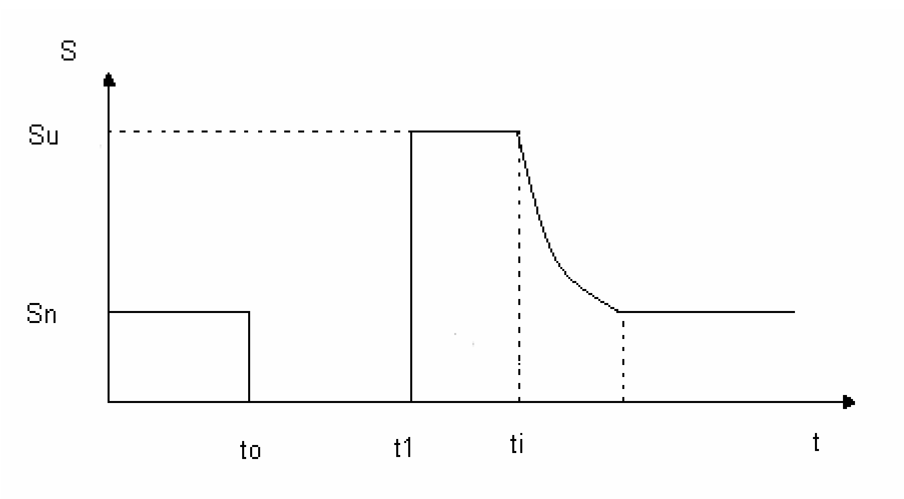

Figure 5 : Load behavior during cold load pick-up

Immediately after restoration, the load remains constant for a short time and then decreases exponentially in time. The load decreases, as it becomes diverse. This behavior could be modeled with a delayed exponential model.
Mathematically, it could be described as:

$$Si(t)=(Sn + (Su-Sn)e^{(-\alpha (t-ti)}) 1(t-ti)+ Su(1-1(t-ti))1(t-Ti) \qquad (4)$$

$$Su=Sn\ R \qquad (5)$$

where the symbols denote the following:

$S_i(t)$ load of i-th feeder
S_n load in normal operation without autage
S_U amount of undiversified load at the moment the supply is restored

α rate of load diversity restoration
1 (t) unit step function
t_0 start of the outage time
t_1 supply is restored
t_i time when diversity starts to reemerge
R ratio between thermostatically-and manually controlled devices.

Load of each feeder is therefore a function of load in normal operation,time and the ratio between thermostatically-and manually controlled devices.

4. FIELD TEST

In order to study their aggregate behavior field measurements have been performed.
Figure 6 shows a measurement performed in the residential area Brnj with 37 consumers in March 2003.g.The interruption in the power supply lasted for 1 hour and the outside temperature was about 5 °C. It is shown that the power consumption is almost 3 times the normal power consumption and it takes 1-2 hours before it is back to a normal level.
The behavior of load during CLPU for the substation in Studentski dom 10/0,4 kV with 195 consumers network was measured during an overhaul of substation in March 2003.g., Fig. 7. The interruption in the power supply lasted for 5 hour and the outside temperature was about 10°C.
At the moment of restoration,the initial load was approximately 2.5 times greater than load before outage. The time after diversity starts to reappear was around 5 minutes, complies with the assumptions in the delayed exponential model. The behavior can be compared with figure 1 and 2 (refrigerators and freezers) although the field test showed a faster recovery.

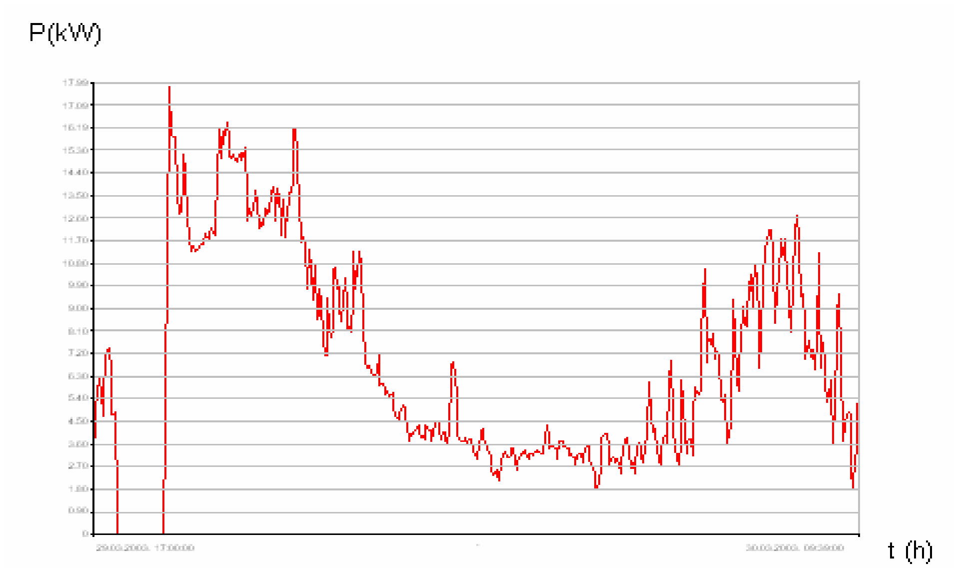

Figure 6: The power consumption of the residential area Brnj following outages of 1 hour

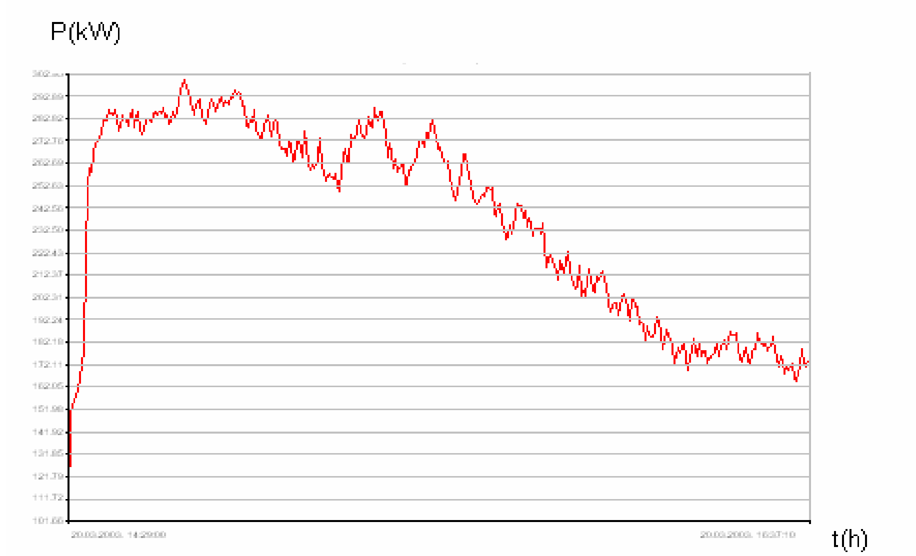

Figure 7: The substation Studentski Dom 10(20)/0,4 kV load behavior in restoration

5.CONCLUSIONS

Prediction of the behavior of residential, commercial and industrial loads is essential to transformer rating, feeder configuration, wire size, sectionalizing, protection requirements, and maintenance and restoration procedures.
This thesis has investigated the dynamic behavior of different types of load used in the residential and industrial sectors following outages. It has then developed mathematical models for such loads, verifying the models against actual field measurements.
For all the industries the power consumption will be lower or much lower after an outage.
Residential load has the opposite behavior as compared with industrial load, i.e. after an outage the load is (much) higher than prior to the disturbance and then decreases to its stationary level. Thermostatically controlled loads such as refrigerators, freezers, air conditioners, electric boilers, electric radiators and heat pumps will loose their diversity after an extended outage and all, or almost all of them, will be in the on state when power is restored. The load peak and its duration are strongly affected by the outage time but for electric heating also the outdoors temperature has a great impact. This is the major reason of the load increase after an outage but the physical behavior of cooling equipment will result in an additional load increase.
The load peak after the outage and its relation to either the rated power (CLPUn factor) or the maximum power experienced during the year (CLPUm factor) is a good indicator of the actual power consumption and can be used when investigating the risk for overloading in a distribution system.
The CLPUn factor, the recovered energy and the derived industrial and residential load models are of interest when studying the cold load pick-up from the transmission point of view. They can therefore be used when formulating restoration guidelines and when tuning a scheme of rotating load curtailment.

Due to the deregulation of the electricity market it is likely in the future that (more) agreements between power suppliers and customers are made which give the power suppliers the possibility to disconnect load when the production capacity is reached or when it is costly to produce the peak power. This may also incorporate the possibility to disconnect load as an alternative to having a turbines for the disturbance power reserve.

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