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Increase of Paper Mill Energy Efficiency by Optimization Energy Supply System Industry

A. Hazi, A. Badea, Gh. Hazi, H. Necula and R. Grigore

Abstract—**Due to the high energy consumption in a paper mill, energy cost is an important part of the overall production cost of paper. Papermaking is a continuous process. Ensuring a continuous energy supply for this process would avoid production losses and supplementary energy consumption for restarting the installations.**

In this paper we develop an optimization model of the energy supply system from the perspectives of reliability and energy loss. Subsequently we use this model to analyze the energy supply system in order to find some solutions for increasing the energy efficiency and for reducing the cost of accidental outages.

***Index Terms*-- energy cost, losses, optimization, paper industry, reliability, system**

I. Nomenclature

AOC annual outages cost ($/year)
EL electricity losses (kWh/h)
ELC energy losses cost ($/year)
ENL energy losses in the energy supply system (KWh/year)
EP electricity price ($/kWh)
HL heat losses (kJ/h)
HP heat price ($/kJ)
IN installations number
K risk of downtime
LPC loss production cost ($/h)
MC cost of removing the outage through manoeuvres ($/outage)
N annual average number of outages (outage number/year)
OC damage function ($)
OT outage duration (h)
P success probability
PR production rate (*kg/h)*
PV production value (*$/kg*)
R set of unsuccessful states
RA set of unsuccessful states transited out from through automatic manoeuvres
RC cost of removing the outage through repairs ($/outage)
RM set of unsuccessful states transited out from through manual manoeuvres
RELC restart energy loss cost ($/h)
RMC raw materials cost (*$/kg)*
RT(OT) restart time (h)
S set of successful states
T duration (h)
TEL total energy losses (kWh/year)
TC total cost ($/year)
q transition intensity (h^{-1})

Greek symbols

λ equivalent failure rate (h^{-1})

Subscripts

AAR automatic closing of the reserve
r repair
k installation

II. Introduction

ENERGY plays a very important role in the production of paper, accounting for 25% to 30% of production costs.

The main energy forms that are needed in the production process are electricity and steam.

Electricity in paper industry is mainly consumed for the operation of various motor drives and for refining the material. Process heat in paper industry is mainly used for evaporating water in the paper drying process, for the heating of water, air and chemicals, for covering the heat loss to the surroundings and for conversion into electricity, [1]. Usually, the steam needed is produced in a Combined Heat and Power plant (CHP) which also generates a part of the needed electricity. The rest of the electricity is purchased from the public grid.

Low specific energy consumption may be achieved by keeping an even and high production level. The reliability of the energy supply system is very important for keeping the paper machines running continuously.

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Therefore we develop an optimization model based on the reliability indices of the energy supply system. Since energy losses in energy-supply systems are different for different schemes, these losses are included in the model.

One element that reliability and energy losses have in common is the cost. Therefore the objective function of the problem is to minimize the total cost, which is composed from the cost of outages and from the cost of energy loss.

In this paper we used the optimization model developed for the analysis of the electricity supply system. The goal of this analysis is to find solutions for reducing the losses due to accidental outages and for increasing energy efficiency.

III. OPTIMIZATION MODEL OF THE ENERGY SUPPLY SYSTEM

Optimization is a widely used way to study industrial energy supply systems. An optimization model is developed using reliability indices. The objective of the optimization is to minimize the total cost, which includes the cost of outages and the energy loss.

Reliability indices

The reliability indices of the electricity supply systems are evaluated using the Marcovian technique. The success state is ensured if all receivers are supplied with electricity.

The main reliability indices that have been evaluated and used in the optimization method are the following, [2], [3]:

-The average annual number of outages that are removed through repairs, N_r:

$$N_r = \left[\sum_{i \in S} \left[P_i \cdot \sum_{j \in R} q_{ij} \right] \right] \cdot T \quad (1)$$

where P_i- probability of i state, q_{ij} – transition intensity from i state to j state, T=8760 h/year is the reference duration.

The probability P_i is evaluated by solving the following equation system:

$$\begin{aligned} &\sum_{i=1}^{n} P_i \cdot q_{ij} = 0, \quad j = 1,2...,n-1 \\ &\sum_{i=1}^{n} P_i = 1 \end{aligned} \quad (2)$$

where n is the total number of states.

-The average annual number of outages that are removed through manual manoeuvres, N_m :

$$N_m = P \cdot \lambda_{me} \cdot T \quad (3)$$

where P - success probability is:

$$P = \sum_{i \in S} P_i \quad (4)$$

and λ_{me} – equivalent failure rate when performing manoeuvres is:

$$\lambda_{me} = \sum_{\substack{i \in S \\ j \in RM}} \lambda_{ij} \quad (5)$$

where λ_{ij} – failure rate of the elements which determine a transition from the successful state i to the unsuccessful state j; this latter state would be transited out from through manual manoeuvres.

-The annual average number of outages that are removed through automatic manoeuvres, N_{AAR}, is calculated as (3) where:

$$\lambda_{me} = \sum_{\substack{i \in S \\ j \in RM}} \lambda_{ij} \cdot \left(1 - K_{AAR}\right) \quad (6)$$

where K_{AAR} is the risk of automation downtime

-The annual average duration of one outage that is removed through repairs, T_r:

$$T_r = \frac{(1-P) \cdot T}{N_r} \quad (7)$$

The annual average duration of one manoeuvre, T_m is established depending on exploitation concrete conditions.

Also, the annual average of the total outage duration, T_{an} is calculated as:

$$T_{an} = N_r \cdot T_r + N_m \cdot T_m \quad (8)$$

Damage functions

In the continuous industrial process, electricity supply outage leads to, among others, lost production and energy losses in the process restart. The probable damages caused by interruptions in the supply of electricity depend on the duration and frequency of outages.

The damage function for every installation k can be represented as:

$$OC_k = LPC_k \cdot \left(OT + RT_k(OT)\right) + RELC_k \cdot RT_k(OT) \quad (9)$$

where restart time $RT_k(OT)$ is dependent on the outage duration, OT.

These costs can be estimated as:

$$LPC_k = \left(PV_k - RMC_k\right) \cdot PR_k \quad (10)$$

$$RELC_k = EL_k \cdot EP + HL_k \cdot HP \quad (11)$$

The total damage function, OC, is estimated as the sum of all the damage functions:

$$OC = \sum_{k=1}^{IN} OC_k \quad (12)$$

Because supply can be restored through repairs or through manoeuvres, the mathematical expression of the annual outages cost (AOC) is derived in the following way:

$$AOC = N_r \cdot RC + \left(N_m + N_{AAR}\right) \cdot MC \quad (13)$$

RC and MC are estimated using the damage functions of the installations. They depend on T_r and, respectively, T_m, both representing the outage duration. MC is the same for the outages that are removed through manual or automatic manoeuvres.

The objective function

Taking into account the energy losses in the energy supply system, the objective function (total cost) can be expressed as, [4]:

$$TC = AOC + ELC = \min! \quad (14)$$

where

$$ELC = ENL \cdot EP \quad (15)$$

The constructive and working constraints are also included into the optimization model.

IV. NUMERICAL RESULTS

The steam needed by the paper mill is being produced by the Combined Heat and Power plant. The CHP plant also produces a small part of the needed electricity, while the remaining electricity needed is purchased from the public grid.

The electricity supply system on 6 kV, figure 3, was analyzed using the optimization model above.

First, we estimated the damage functions for the main installations: the newsprint machine (M2), the toilet paper machine (M1) and the owned CHP, using relation (7). After that, the total outage function was estimated. These damage functions are shown in the figures 1 and 2.

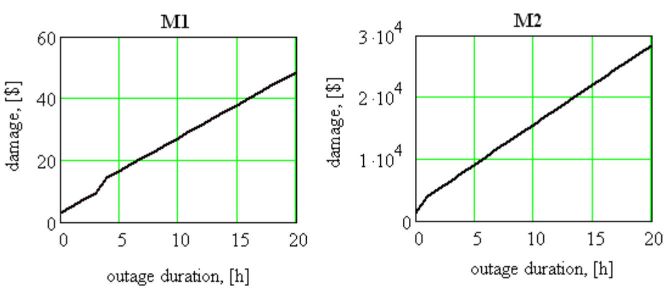

Fig. 1. The M1 and M2 damage functions

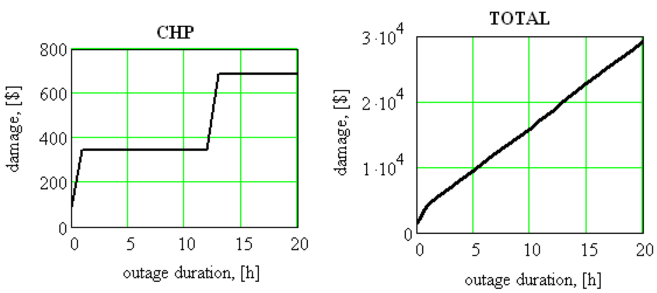

Fig. 2. The CHP damage function and the total damage function

Note, damage of M1 and CHP are much lower than damage of M2. The total damage is mainly determined by the M2 damage.

For the optimization of the electricity supply system, the following constraints are imposed, [5]:

1. time difference between two successive protection steps;
2. short circuit currents must be under the breaking capacity of existing circuit-breakers;
3. short circuit currents must be smaller than the rated thermal current of the cables/lines.

In order to increase reliability and to decrease energy losses we propose energy supply system changes:

- change the supply of M1 from substation CET II to substation SRA
- supply M1 with two feeders: from bus bar IA and from bus bar IB
- remove substation CET II and feeders L7, L8, L9

These changes are possible because energy supply systems were designed for 12 paper machines and now, only two paper machines work in the paper mill. Thus, now there are empty cells in the SRA substation. Also, M1 was moved near SRA and the resulting protection stages are bigger than in the initial scheme.

The initial scheme and the proposed scheme are presented in figure 3 and figure 4, respectively.

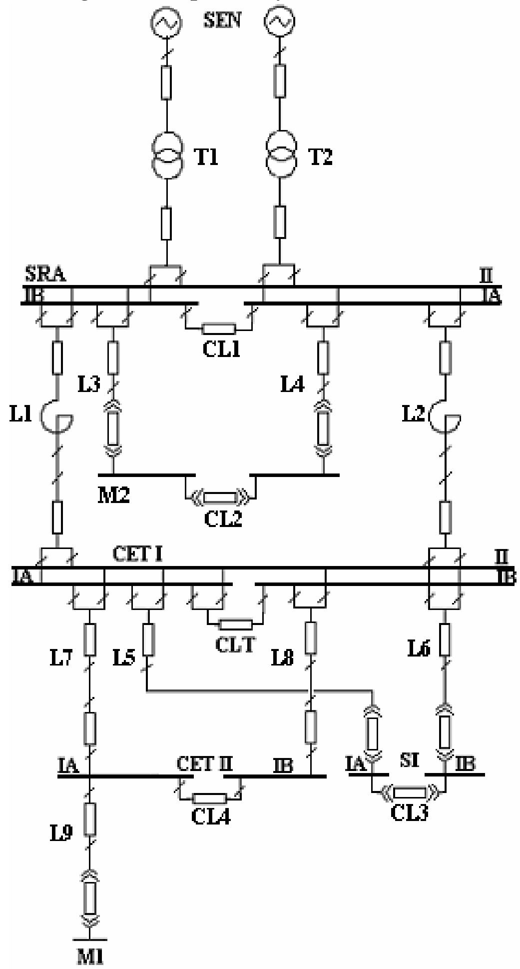

Fig. 3. The initial electricity supply system

We calculated the reliability indices and electricity losses for each system in the three working variants. These three variants depend on the number of 110/6kV transformers (T1 and T2), on the supply feeders number (L1…L11) and on the switches position in the longitudinal couples (CL1…Cl4).

- variant 1 - T1, SRA-IA, M2 and T2, SRA-IB, CETI. The longitudinal couple CL1 is open and all others are closed.
- variant 2 – T1, SRA-IA+IB and T2 do not work but they are in warm reserve, equipped with AAR (automatic closing of the reserve). All longitudinal couples are closed. The warm reserve means the disconnectors on the high voltage and on the medium voltage of the transformer are closed while the circuit-breakers are opened and they can be closed by the AAR.
- variant 3 – T1, SRA-IA+IB and T2 do not work but they are in warm reserve, equipped with AAR. The longitudinal couples CL1 and CL2 are closed. Other couples are open and are equipped with AAR.

The annual average duration of one manoeuvre was considered, for all variants, to be $T_m = 0.5$ h/outage.

After that we estimated the objective function. Results are presented in the tables I…VI.

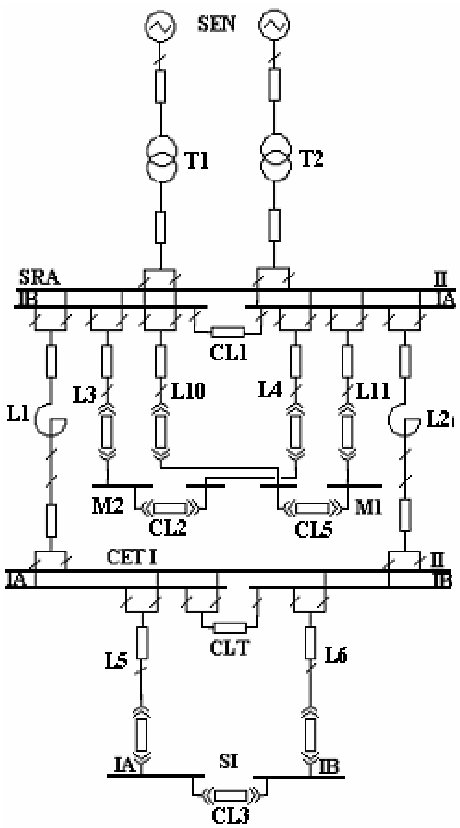

Fig. 4. The proposed electricity supply system

TABLE I
RELIABILITY INDICES FOR THE INITIAL SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Annual average number of outages that are removed through repairs	N_r	outages number/ year	0.0204	0.0204	0.0204
Annual average number of outages that are removed through manual manoeuvres	N_m	outages number/ year	2.0804	1.561	0.311
Annual average number of outages that are removed through AAR	N_{AAR}	outages number/ year	0	0.357	1.408
Annual average of the total duration of outages	T_{an}	h/year	1.628	1.368	0.781

TABLE II
RELIABILITY INDICES FOR THE PROPOSED SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Annual average number of outages that are removed through repairs	N_r	outages number / year	0.0174	0.0174	0.0174
Annual average number of outages that are removed through manual manoeuvres	N_m	outages number/ year	2.7496	1.4716	0.385
Annual average number of outages that are removed through AAR	N_{AAR}	outages number/ year	0	0.357	1.408
Annual average of the total duration of outages	T_{an}	h/year	1.882	1.243	0.6994

TABLE III
ANNUAL ENERGY LOSSES FOR THE INITIAL SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Energy losses in the energy supply system	ENL	MWh	1068.0	669.0	669.0
Energy losses in the installations	EL	MWh	3.4	3.2	2.8
Heat losses in the installations	HL	MWh	21.9	20.2	18.2
Total energy losses	TEL	MWh	1093.3	692.4	690.1

TABLE IV
ANNUAL ENERGY LOSSES FOR THE PROPOSED SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Energy losses in the energy supply system	ENL	MWh	1066.0	667.0	667.0
Energy losses in the installations	EL	MWh	4.5	3.0	2.9
Heat losses in the installations	HL	MWh	28.6	19.2	18.9
Total energy losses	TEL	MWh	1099.0	689.2	688.8

TABLE V
ANNUAL COST FOR THE INITIAL SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Annual outages cost	AOC	$	5910	5515	5031
Energy losses cost	ELC	$	87869	55042	55042
Total cost (objective function)	TC	$	93779	60556	60072

TABLE VI
ANNUAL COST FOR THE PROPOSED SYSTEM

Parameter	Symbol	Unit	Value		
			Var. 1	Var. 2	Var. 3
Annual outages cost	AOC	$	7421	5180	5094
Energy losses cost	ELC	$	87705	54877	54877
Total cost (objective function)	TC	$	95125	60057	59971

We note that the number of faults removed through repair is very low due to the large number of supply variants for the main installations.

Introducing the automatic closing of the reserve leads to less interruptions removed through manoeuvres and thus reduces the annual total duration of outages. In variant 3, the annual total duration of outages is decreased by almost 50%.

Energy losses are, in large part, due to losses in transformers 110/6 kV of the SRA, which are less loaded. Switching to reserve one of them leads to a significant decrease in energy losses. In this case, due to the introduction of AAR, the reliability in operation is not affected.

The weight of the energy losses due to the restart of installations is small (around 3%; heat losses are the most important). This is explained by the small number of outages due to lack of supply as a result of a good reliability of the energy supply. But the weight of the cost of outages is somewhat higher (8-9%) because it includes the cost of production losses.

The proposed system offers a lower total cost than the initial system only in variants 2 and 3. Variant 3, having the lowest total cost, is the best.

V. Conclusions

The reliability of the electricity supply system for industrial consumers has important economical implications. This determines the frequency and duration of accidental outages.

Using optimization model presented in this paper, without further investments, we can minimize the damage from unsupplied consumers by selecting the proper working scheme. In choosing the optimal operating scheme we must also take into account the energy losses in the supply system. In the analyzed case they have the largest weight in the total loss. We can only get to the optimal solution by correlating the installations energy losses with their reliability of the energy supply system. For example, in the analyzed case, if we apply variant 3 to the scheme we can obtain energy savings of up to 401 MWh / year and reduce the total cost by up to 32,992 $ / year.

VI. References

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VII. Biographies

Prof. A. Hazi, PhD, graduated from Faculty of Electrotechnics of University Gh.Asachi of Iasi, specialization Industrial Energetics in 1982. In 1999 obtained the scientific title of doctor engineer of the University Politehnica of Bucharest, specialization Thermoenergetics.
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Prof. A. Badea, PhD, graduated from Faculty of Power Engineering of University Politehnica of Bucharest, specialization Thermoenergetics in 1968. Doctor engineer since 1974, has an outstanding teaching, scientific and technical activity in the fields of heat transfer, thermal equipment and installations. Ph.D. coordinator since 1993, has managed to create in the university a strong school in the field of equipment and thermal installations with important collaboration in the country and abroad. Now, he is vice-rector of the University Politehnica of Bucharest.

Prof. Gh. Hazi, PhD, graduated from Faculty of Electrotechnics of University Gh.Asachi of Iasi, specialization Industrial Energetics in 1982. In 1997 obtained the scientific title of doctor engineer of the University Gh.Asachi of Iasi, specialization Electroenergetics.
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Associated Professor, H. Necula, PhD, graduated from Faculty of Power Engineering of University Politehnica of Bucharest, specialization Industrial Energetics in 1993. In 1999 obtained the scientific title of doctor engineer of the National Institute of Applied Sciences in Lyon and the University Politehnica of Bucharest, specialization Thermoenergetics. Since 1993 teacher at the Faculty of Power Engineering and has an intense teaching and scientific activity in the fields of heat and mass transfer, heat exchangers and refrigeration installations. Now, he is the head of Department of Generation and Use Energy of University Politehnica Bucharest.

Lecturer R.Grigore, PhD, graduated from Faculty of Power Engineering of University Politehnica of Bucharest, specialization Thermoelectric Power Plants in 1991. In 2008 obtained the scientific title of doctor engineer of the University Politehnica of Bucharest, specialization Power Engineering.
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