Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

Transformers Efficiency Variability in Energy Hub Modelling

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ABSTRACT

This paper presented an energy hub model considering the impact of transformer efficiencies, by taking the difference in transformer efficiency based on the load demand. This can be achieved by taking the transformer efficiency as a dynamic value according to the transformer loading efficiency curve, as the transformer efficiency differs due to the copper losses. The following energy hub model was solved using Mixed Integer Linear Programming (MILP) with a CPLEX solver in GAMS software. Final findings showed that there is only a slight difference in the final overall when taking transformer efficiency variety into consideration for one transformer.

Keywords: transformer efficiency, energy hub, multiple energy carriers, optimal operation, optimization

NONMENCLATURE

Abbreviations	
MILP	Mixed Integer Linear Programming
EH	Energy hub
CHP	Combined Heat and Power
LOLE	Loss of Load Expected
LPSP	Loss of Power Supply Probability
Symbols	
Of	Objective function
$E_g^{CHP}(t)$	The amount of bought gas for CHP
$E_g^{Bo}(t)$	The amount of bought gas for CHP
$Pc(t)$	Electricity price
Pg	Gas Price
$E_e^{Gr}(t)$	The amount of bought electricity from the grid
$E_e(t)$	Electricity demand
$E_e^{CHP}(t)$	Electricity produced by CHP
μ_e^{CHP}	CHP electrical efficiency,
$E_e^{Wind}(t)$	Electricity from the wind turbine
$E_e^{DR}(t)$	Electricity from the demand response
$E_e^{Bch}(t)$	Battery charging
$E_e^{Bds}(t)$	Battery discharging
μ_e^{TR}	Transformer with an efficiency
$E_H(t)$	Heat demand
μ_g^{CHP}	CHP heat generation efficiency
μ_g^{Bo}	Boiler efficiency
$E_g(t)$	The amount of gas purchased
E_g^{Max}	Maximum capacity of the gas network
E_e^{Max}	Maximum capacity of the electricity network
E^{TR}	Maximum capacity of the transformer
E^{CHP}	Maximum capacity of the CHP
E^{Bo}	Maximum capacity of the boiler
$E_e^{B}(t)$	battery charge at any hour
E^{B}	Maximum capacity of the battery
$S_e^{ch}(t)$	Binary battery charging status
$S_e^{ds}(t)$	Binary battery discharging status
μ_e^{ch}	Charging efficiency
μ_e^{ds}	Discharging efficiency
$E_e^{up}(t)$	The net amount of shifted electricity up
$E_e^{down}(t)$	The net amount of shifted electricity down
μ_e^{up}	The allowed amount of electricity shifting up
μ_e^{down}	The allowed amount of electricity shifting down
$\mu_e^{TR}(t, D_e)$	The changing transformer efficiency based on loading by having the term

1. INTRODUCTION

A combination of different energy sources (e.g. converters, renewable energy, and energy storage systems) can be connected forming an energy hub . This concept has become popular in recent years as a way to maximize efficiency, reliability, security, and sustainability and minimizing the operating cost and pollution emissions.

In the earlier days EH was considered as a black box having energy as inputs and outputs. As more interest was formed in the literature regarding EHs, various structures were proposed. Having the count and/or citing of components inside the EH as the main difference. In a very simple EH structure was proposed containing a transformer, wind turbine, CHP, and a boiler. Having electricity and natural gas as inputs, and heat and electricity as outputs.

A more complex structure in adds a thermal storage component to the hub, water and gas as extra inputs and outputs to the system. Other scholars have studied the integration of more components. Most of the before-mentioned studies have the main concern of minimizing operational and/or planning costs. The optimization time frame for the EHs was used as 24 hours earlier, but nowadays time frames of years divided by seasons are more on the rise. Aspects of energy hubs security were investigated in [1]–[4].Recently the trend of research on the topic of energy hubs is going more in the favor of the control schemes as introduced in [5]–[7].

In most of the literature, the energy hub is modeled as mathematical equations having demands as inputs to the optimization problem which outputs energy scheduling/loading on each component in the system. The demands are at the most of time declared in tables or graphs obtained from real live data (e.g. wind speeds for a certain wind turbine location). On the other hand, constraints for the energy hub models are a state-of-the-art topic. As in earlier models detailed and well-investigated network constraints were not implemented. But nowadays some scholars have introduced sufficient constraints for the network side (usually input side). Mohammadreza Daneshvar et al. in [8] has taken into consideration the gas pipe constraints, by which compressors ratings and pressure limits were implemented.

Many studies have investigated energy hub scheduling and planning assessments based on numerical and simulation methods [9]–[12]. Optimization of a long-term energy hub expansion planning model for multiple energy networks consisting of electricity, natural gas, and district is studied in [9], which determines the least-cost planning schedule of candidate CHPs, generating units, transmission lines, and natural gas furnaces. In [10] and [12], a mathematical optimization model for residential energy hubs in presence of a smart grid and automated decision making technologies is proposed, which not only minimize energy demands and total cost of energy consumption but can also reduce emissions and peak load of the hubs. All these efforts build the scheduling models on deterministic optimization and do not take into account uncertainties of renewable resources. Considerable efforts have been devoted to the operational and economic impact of wind power uncertainty on the energy hub planning and scheduling problems. In [11], an optimal operating model for an energy hub considering the uncertainty of wind, price, and demand is proposed.

The energy hub models consist of various components mathematically represented as variables multiplied by the component efficiency. The efficiency of each component is essential as components in an EH have losses when converting energies from a form to another. The anergy concept denotes the unused energy as the waste heat of combustion processes, unlike exergy that indicates the amount of usable energy. As stated in [13] and [14], The part of available work which is truly utilized is indicated by exergy efficiency, the exergetic efficiency of a system or device is defined as the ratio between the actual utilized exergy (output) and the input exergy flow into the system. In all of the EH models mentioned above the efficiency of each component is modelled as a constant. Indicating that the anergy of any component is constant regardless of the loading if the component. Which is not true; as especially transformers are known for having various efficiencies based on the loading percentage[13].

Transformers played a substantial role in transmitting and receiving power inside the hugest mankind build power delivery network. Those machines rely on the magnetic coupling between different coil windings to step voltages up or down through specially designed cores. However, the conversion efficiency of energy and the stability under various operation conditions for those devices always raised a concern. Fig.1 shows the basic equivalent circuit of a transformer, in this circuit R1 and X1 corresponds to the primary winding resistance and leakage reactance, while R2 and X2 represents the secondary winding resistance and leakage reactance as in Fig.1. The core loss resistance is presented as R0 while X0 solidifies magnetizing reactance, both can be determined by the open circuit test of a transformer.

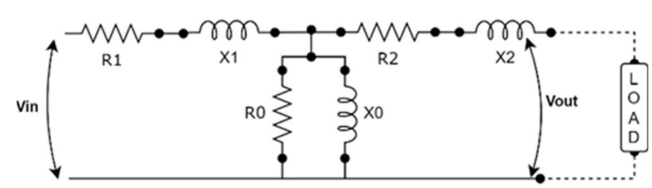

Fig.1.Basic Equivalent Circuit of A Transformer

The transformers efficiency varies with the loading percentage as shown in Fig.2. In which the efficiency reaches a maximum at a certain load then it decreases. The maximum transformer efficiency is archived when load and no-load losses are equal [13].

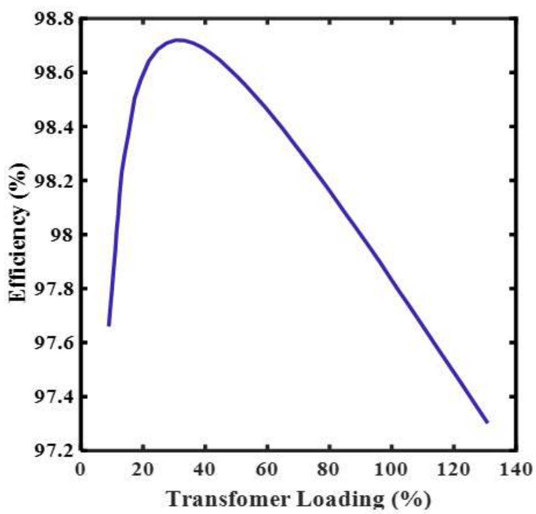

Fig.2.Transformer Efficiency and Loading Percentage

This paper investigates the effect of considering the various efficiencies of transformers based on the loading percentage. The remainder of the paper is presented as the following: In section II, the energy hub concept was presented with its operating principle. Section III provides the mathematical model for the proposed energy hub. Subsequently, section IV highlights the final findings and outcomes of the proposed energy hub system. Lastly, in Section V, the paper concludes with an overview of its future direction.

2. CONCEPTUAL MODEL OF THE ENERGY HUB

The proposed EH model used in this paper is shown in Fig. 3. The energy inputs to the EH are the electricity and natural gas networks. The EH has two types of loading, electrical and heat. The loads (demands) can be fulfilled by a combination of one or more of the components inside the EH.

The electrical demand can be delivered by either buying electricity form the grid, passing it through a transformer, converting gas to electricity via a CHP, local wind turbine, battery and/or demand response. The wind turbine output power per hour was directly fed to the model. The demand response with tolerance of 2% of the demand is used to shift the load up or down based on the demand volume. The energy storage system resembled by the battery is utilized to store electrical energy in off-peak hours and excess wind generated energy then discharge when needed. The heat demand is addressed by the combination of a CHP and boiler fed by the natural gas network. The boiler is used to fulfill the heat demand when the CHP is used for generating electricity of high amounts. All the components in the proposed EH model were utilized with a single constant efficiency value, except for the transformer as demonstrated below.

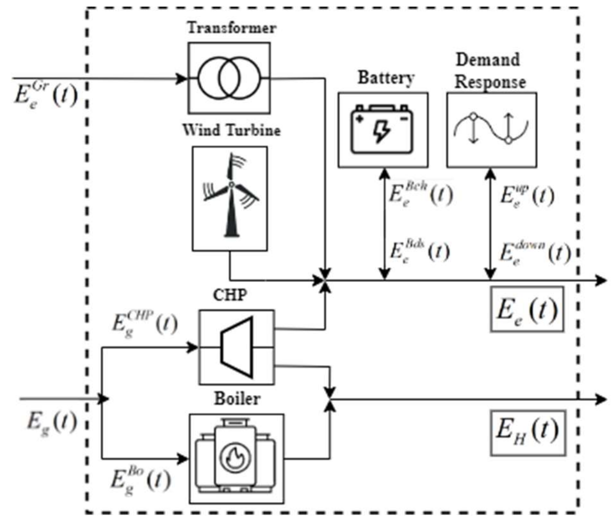

Fig. 3. EH Modeled in This Study

3. MATHEMATICAL MODELLING

To investigate the effect of taking into consideration the variable efficiencies of the transformer, two models were built. The proposed EH models studied in this paper are based on the model presented in [15]. The first model has constant transformer efficiency of 98.7%, while the other model utilizes the various efficiency values depending on the loading percentage.

3.1 Static Transformer Efficiency Model

The Objective Function (1) consists of the amount of bought electricity$E_e^{Gr}(t)$ and gas for CHP$E_g^{CHP}(t)$ and boiler $E_g^{Bo}(t)$ from the network multiplied by their prices $Pc(t)$ and Pgrespectively.

$$Of = Pc(t)E_e^{Gr}(t) + Pg(E_g^{CHP}(t) + E_g^{Bo}(t)) \quad (1)$$

Equation (2) shows that the electricity demand $E_e(t)$ must be fulfilled by electricity bought from the grid$E_e^{Gr}(t)$, electricity produced by CHP $E_e^{CHP}(t)$ with μ_e^{CHP} electrical efficiency, wind turbine $E_e^{Wind}(t)$, demand response $E_e^{DR}(t)$, battery charging $E_e^{Bc}\ (t)$ and discharging$E_e^{Bds}(t)$. The electricity bought from the grid is fed to a transformer with an efficiency of μ_e^{TR}.

$$E_e(t) = \mu_e^{TR} E_e^{Gr}(t) + \mu_e^{CHP} E_e^{CHP}(t) + E_e^{Wind}(t) + E_e^{DR}(t) + E_e^{Bds}(t) - E_e^{Bc}\ (t) \quad (2)$$

The heat demand $E_H(t)$ is fulfilled by CHP heat output $E_g^{CHP}(t)$ with heat generation efficiency of μ_g^{CHP} and boiler heat output $E_g^{Bo}(t)$ with μ_g^{Bo} efficiency in (3). The amount of gas purchased $E_g(t)$ is limited to CHP and boiler usage in (4).

$$E_H(t) = \mu_g^{CHP} E_g^{CHP}(t) + \mu_g^{Bo} E_g^{Bo}(t) \quad (3)$$

$$E_g(t) = E_g^{CHP}(t) + E_g^{Bo}(t) \quad (4)$$

Equations (5)-(10) are constrains for the EH various capacities. Where E_g^{Max} and E_e^{Max} are the capacities of the gas and electricity networks respectively in (5) and (6). The transformer, CHP capacities and boiler E^{TR} in (7), E^{CHP} in (8) and E^{Bo} in (9) are limited by the amount of energy conversion scaled by each equipment efficiency. Equation (10) limits the battery charge at any hour $E_e^B(t)$ by its maximum capacity E^B.

$$E_g(t) \le E_g^{Max} \quad (5)$$

$$E_e(t) \le E_e^{Max} \quad (6)$$

$$E_e^{Gr}(t)\mu_e^{TR} \le E^{TR} \quad (7)$$

$$E_g^{CHP}(t)\mu_g^{CHP} \le E^{CHP} \quad (8)$$

$$E_g^{Bo}(t)\mu_g^{Bo} \le E^{Bo} \quad (9)$$

$$0 \le E_e^B(t) \le E^B \quad (10)$$

The energy in the battery at any hour is declared in (11) and limited by (12) and (13) where $S_e^{ch}(t)$ and $S_e^{ds}(t)$ are binary variables for the battery states supported by the discharging and charging efficiencies μ_e^{ds} and μ_e^{ch}.

$$E_e^B(t) = E_e^{Bch}(t) - E_e^{Bds}(t) + E_e^B(t-1) \quad (11)$$

$$0 \le E_e^{Bch}(t) \le E^B S_e^{ch}(t)(1/\mu_e^{ch}) \quad (12)$$

$$0 \le E_e^{Bds}(t) \le E^B S_e^{ds}(t)\mu_e^{ds} \quad (13)$$

Equation (14) assures that the net amount of shifted electricity up $E_e^{up}(t)$ and down $E_e^{down}(t)$ demands response for a full day are equal. Limited by the allowed amount of electricity shifting up μ_e^{up} and down μ_e^{down} in (15) and (16).

$$\sum_{t=1}^{24} E_e^{up}(t) - \sum_{t=1}^{24} E_e^{down}(t) = 0 \quad (14)$$

$$0 \le E_e^{up}(t) \le E_e(t) S_e^{up}(t)\mu_e^{up} \quad (15)$$

$$0 \le E_e^{down}(t) \le E_e(t) S_e^{down}(t)\mu_e^{down} \quad (16)$$

3.2 Dynamic Transformer Efficiency Model

The second model utilizes all the equations used in the first model, but instead of (2), (17) is used. Equation (17) utilizes the changing transformer efficiency based on loading by having the term $\mu_e^{TR}(t, D_e)$. In which the efficiency is changes over time and its value is determined by the electrical demand to be supplied by the transformer from the electricity network.

$$E_e(t) = \mu_e^{TR}(t, D_e)E_e^{Gr}(t) + \mu_e^{CHP} E_e^{CHP}(t) + E_e^{Wind}(t) + E_e^{DR}(t) + E_e^{Bds}(t) - E_e^{Bch}(t) \quad (17)$$

4. SIMULATION RESULTS AND DISCUSSION

The above energy hub model was solved using MILP CPLEX solver in GAMS software. The model was solved twice, once having the transformer efficiency as a constant then having the term $\mu_e^{TR}(t, D_e)$ which resembles efficiency of the transformer varying with respect to the loading as in Fig.2. Fig. 4 and 5 show how the electrical demand is fulfilled by the various electrical vectors inside the EH. The red line indicates how much electricity is needed to be fulfilled by the various generation units (wind turbines, electricity from the grid, battery, demand response, and CHP). Where the black line indicates the amount of electricity taken from the electrical grid, while the livid line displays the converted electricity from the purchased gas by the CHP, the blue line illustrates the generated electricity by the wind turbine, battery contribution to the EH is shown by the green line, and the pink line represents the demand response of the system.

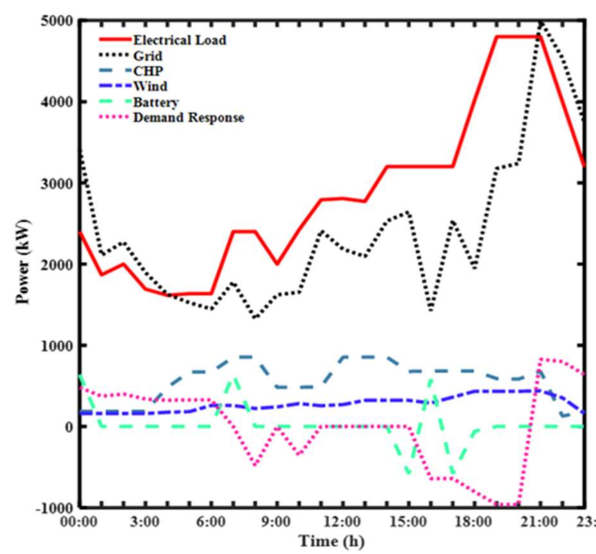

Fig.4.Electricity Demand Fulfillment Distribution Based on Static Transformer Efficiency

In Fig.4 transformer efficiency had considered as a fixed (static) value for all the different electricity demands, which is not accurate as the efficiency of the transformer varies with the load. While the difference in transformer efficiencies according to the variability in electricity demand is in Fig.5. In which the transformer efficiency varies as in Fig. 2, and it is noticeable that when the load increases the transformer efficiency decreases due to the increase in the copper losses since the transformer efficiency is the ratio between the output power to the input power plus losses.

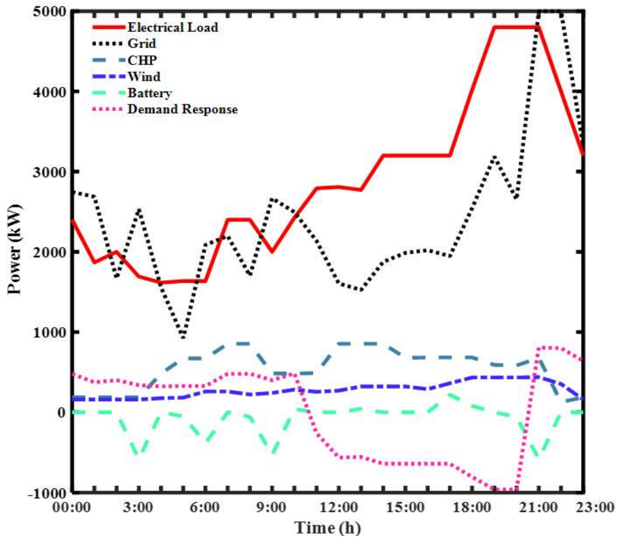

Fig. 5. Electricity Demand Fulfillment Distribution Based on Dynamic Transformer Efficiency

The main differences between the two scenarios can be noticed in the profile of the purchased electricity from the network and the battery charging and discharging but the purchased electricity is more of interest as this electricity directly correlates to the final total operational cost.

To further investigate the above, the amount of electricity withdrawn from the network which had illustrated in Fig.6, as the red line on the graph illustrates how much electricity is supplied by the network without taking the variation in the transformer efficiency into account, while the blue line reflects how much electricity comes from the network when transformer efficiency is considered as a variable value depending on demand which correlates to the transformer loading. Figure 6 proves that the profile of the purchased electricity from the grid differs. As both models contribute to fulfill the demand; but at most of the 24 hours period there were notable differences in the profiles. This directly correlates to the operational cost. The static efficiency model had a total cost of 1219661 USD, while the dynamic efficiency model had a total cost 1218790 USD. The deviation between both costs is not very high; but in the case of having tens of transformers instead of one as proposed in this model; the deviation would be much higher. Which indicates that proper consideration of the transformer efficiency results in less overall cost of EH operation.

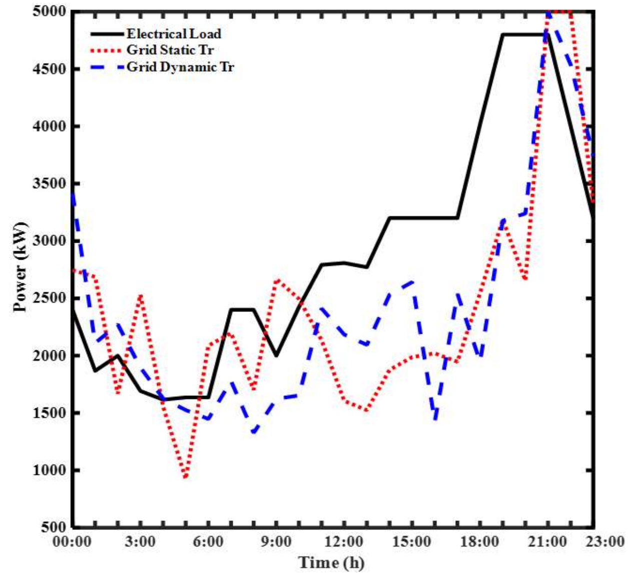

Fig. 6. The amount of electricity taken from the grid to meet the demand

The authors of [16] introduced an uncertainty model that is concerned with the purchased electricity price, demand, and wind uncertainties. The evaluation of the role of uncertainties was well investigated by implementing various reliability indices such as the Loss of Load Expected (LOLE) and Loss of Power Supply Probability (LPSP). In [17] and [18] the uncertainties in EH's are investigated on building a robust modeling scheme and demand response uncertainty respectively. In the literature there is not a comprehensive investigation that takes into consideration the uncertainty of the EH components behavior and characteristics.

5. CONCLUSION

This work investigated the effect of transformer efficiency on the final overall operational cost by taking the difference in transformer efficiency according to the load demand into consideration. Lastly, the final result of this work indicates that the cost difference between the two models was not high when using one transformer, but it is worth noting that the difference will be very apparent if many transformers are used. Especially in distribution grids tens of transformers are utilized. The cost difference gives an indication that the various uncertainties of EH components can accumulate to yield in a higher deviation of operation or planning of EH.

There are various uncertainties in EH components such as the batteries degradation over time, CHP heat pipes losses, electricity transmission lines losses and much more. Future work will be based on building a more complex EH model that takes into consideration most of the uncertainties aided with reliability evaluation.

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