CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791

DOI: 10.3303/CET1335083

A Process Integration Technique for Targeting and Design of Off-grid Hybrid Power Networks

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A mathematical programming approach is established for the analysis and design of the off-grid hybrid power system (HPS). A condensed transshipment model (CTM) is first proposed, where the problem of allocating the power sources to demands as well as the storage of excess electricity for later use is formulated as a linear programming (LP) model. The CTM is further extended to the expanded transshipment model (ETM), also formulated as a linear programming model, for providing more detailed source-sink matching information. An illustrative case study taken from Wan Alwi et al. (2012) is solved to demonstrate the proposed transshipment models.

1. Introduction

Pinch analysis has been a well-established process integration methodology for targeting of various resource conservation systems. The pinch analysis technique has been applied for targeting the recovery of various resources, such as heat (Linnhoff et al., 1982), heat and power (Klemeš et al., 1997), mass (El-Halwagi and Manousiothakis, 1989), and water (Wan Alwi et al., 2012). Recently, Wan Alwi et al. (2012) extended the generic pinch concept to power systems analysis for targeting the minimum outsourced and excess electricity for off-grid hybrid power systems (HPS). In their analysis, the power composite curves are constructed for the onsite electricity generation (sources) and the equipment electricity consumption (demands). By plotting the source and demand composite curves on a time-electricity diagram and shifting the curves to make them touch at a point (i.e. the pinch point), the targets for outsourced and excess electricity can be found. Although this power pinch analysis provides valuable insights into the HPS, the authors did not show the allocation of the onsite generated and outsourced electricity to the demands.
In this work, a mathematical programming approach will be established for the analysis and design of the off-grid hybrid power system. A condensed transshipment model (CTM) will be first proposed, where the problem of allocating the power sources to demands as well as the storage of excess electricity for later use will be formulated as a linear programming (LP) model. The CTM will be further extended to the expanded transshipment model (ETM), which will be also formulated as a linear programming model, for providing more detailed source-sink matching information. An illustrative case study taken from Wan Alwi et al. (2012) representing the case of an off-grid hybrid power system will be solved to demonstrate the proposed transshipment models.

2. Problem statement

Suppose there are a set of available sources for power supplies ($i \in I$) including the accessible electricity at the specified time intervals, and a set of power demands ($j \in J$) with the obtainable consumption rate within given time intervals. The goal is to find the minimum electricity that should be outsourcing from the public grid and the electricity that can be stored for later use or exported to the public grid. The matching between the power supplies and the electricity demands are also desired.

Please cite this article as: Chen C.L., Lai C.T., Lee J.Y., 2013, A process integration technique for targeting and design of off-grid hybrid power networks, Chemical Engineering Transactions, 35, 499-504 DOI:10.3303/CET1335083

3. Model formulation

The condensed transshipment model (CTM) and the expanded transshipment model (ETM) for analysis and design of the hybrid power system are presented in Figure 1. Therein, a set of time intervals ($k \in K$) are defined based on the given time intervals for power supplies/demands. Those relevant notations can be found in the Nomenclature.

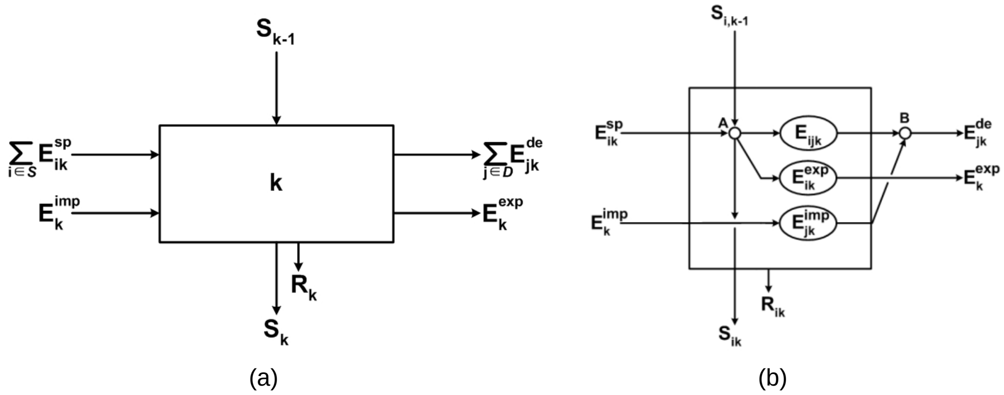


Figure 1: The (a) condensed transshipment mode (CTM) and (b) expanded transshipment model (ETM)

Power balance within each time interval is established by considering available power supplies and demands at each time interval. In the first section, the formulation for the condensed transshipment linear programming model (CTM) subject to the simplifying assumption for each time interval energy balance is presented. Eq(1) describes the power balance for time interval *k*, where S_{k-1} is the available power supply from the previous time interval *k-1* and R_k, residual exiting interval *k*, $\sum_{\forall i \in I} E_{ik}^{\text{sp}}$ and $\sum_{\forall j \in J} E_{jk}^{\text{de}}$, the total available power supply and demand at interval *k*, E_k^{imp} and E_k^{exp}, the required imported/exported power. The redundant Eq(2) is used for emphasizing the current assumption of zero storage loss for electricity.

$$S_{k-1} + \sum_{\forall i \in I} E_{ik}^{\text{sp}} + E_k^{\text{imp}} = R_k + \sum_{\forall j \in J} E_{jk}^{\text{de}} + E_k^{\text{exp}} \qquad \forall k \in K \tag{1}$$

$$S_k = R_k \qquad \forall k \in K \tag{2}$$

$$E^{\text{imp}} = \sum_{\forall k \in K} E_k^{\text{imp}} \tag{3}$$

In addition, we use Eq(4)-(6) for considering various scenarios, including outsourcing at beginning (Eq(4)) or on demanding (Eq(5)), start-up and normal operations (Eq(6)).

$$E_k^{\text{imp}} = 0 \qquad \forall k \in K^- \text{ (for outsourcing at beginning)} \tag{4}$$

$$E_k^{\text{imp}} \geq 0 \qquad \forall k \in K^- \text{ (for outsourcing on demand)} \tag{5}$$

$$S_0 = S_k = 0 \text{ (for start-up); } \geq 0 \text{ (for normal operation)} \tag{6}$$

With the solution space defined by Eq(1)-(6), two-phase LP problems are proposed for obtaining an unique solution. The LP problem with objective function J_1 given in Eq(7) is used to find the minimal outsourcing electricity, $(E^{imp})^*$. With the minimal amount of electricity imported from the public grid as the additional constraint for the second phase optimization, Eq(8) will be applied to minimize the residual electricity for each time interval.

$$\min J_1 = E^{\text{imp}} \tag{7}$$

$$\min J_2 = \sum_{\forall k \in K} R_k \tag{8}$$

Similar LP formulations for the ETM model are given below, Eq(11)-(20), where more detailed matching for electricity supply/demand is available.

$$S_{i,k-1} + E_{ik}^{\text{sp}} = R_{ik} + \sum_{\forall j \in J} E_{ijk} + E_{ik}^{\text{exp}} \quad \forall i \in I, k \in K \tag{11}$$

$$E_{jk}^{\text{de}} = \sum_{\forall i \in I} E_{ijk} + E_{jk}^{\text{imp}} \quad \forall j \in J, k \in K \tag{12}$$

$$S_{ik} = R_{ik} \quad \forall i \in I, k \in K \tag{13}$$

$$E_j^{\text{imp}} = \sum_{\forall k \in K} E_{ik}^{\text{imp}} \quad \forall j \in J \tag{14}$$

$$R_k = \sum_{\forall i \in I} R_{ik} \quad \forall k \in K \tag{15}$$

$$E_{jk}^{\text{imp}} = 0 \quad \forall j \in J, k \in K^- \text{ (for outsourcing at beginning)} \tag{16}$$

$$E_{jk}^{\text{imp}} \geq 0 \quad \forall j \in J, k \in K^- \text{ (for outsourcing on demand)} \tag{17}$$

$$S_{i0} = S_{iK} = 0 \text{ (for start-up)}; \ \geq 0 \text{ (for normal operation)} \ \forall i \in I \tag{18}$$

$$\min J_1 = \sum_{\forall j \in J} E_j^{\text{imp}} \tag{19}$$

$$\min J_2 = \sum_{\forall k \in K} R_k \tag{20}$$

4. Numerical example

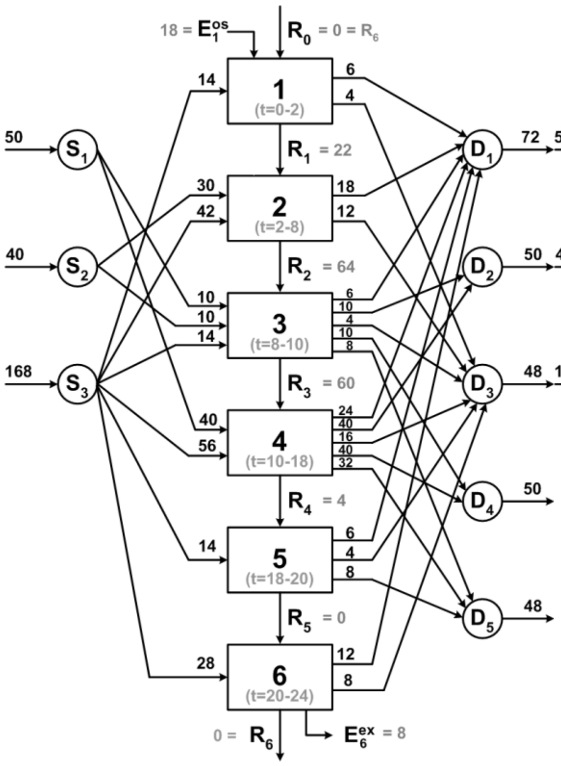
An illustrative example taken from Wan Alwi et al. (2012) is adopted for demonstrate the proposed transshipment models. The available power supplies/demands as well as their working time intervals and ratings are given in Tables 1 and 2. Four scenarios for CTM are studied, including (a) start up operation with outsourcing at beginning; (b) start up operation with outsourcing on demand; (c) normal operation with outsourcing at beginning; and (d) normal operation with outsourcing on demand. Whereas two scenarios for ETM are investigated, including (e) normal operation with outsourcing at beginning; and (f) normal operation with outsourcing on demand. Only those results of using CTM under various scenarios are shown in Figure 2 due to space limitation. The minimal outsourcing electricities are 18 kWh for scenarios of start-up operation and 10 kWh for normal operation. Further to these targeting outsourcing electricities, some valuable information such as those matching between electricity supplies and demands, as well as the electricity residuals on all time intervals, the surplus electricity for exporting to the public grid, are explicitly found by using the proposed LP formulation for the CTM, as shown in Figure 2, and the ETM. Those scenarios considering the possible loss of electricity due to storage are under taken.

Table 1: Power supplies for illustrative example

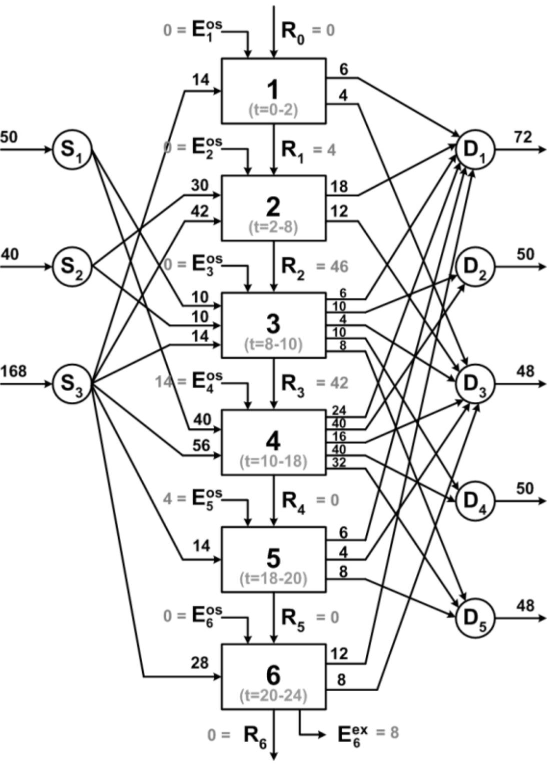
Power supply	Time (h)			Power rating generated	Electricity generation
	from	to	interval	(kW)	(kWh)
Solar	8	18	10	5	50
Wind	2	10	8	5	40
Biomass	0	24	24	7	168

Table 2: Power demands for illustrative example

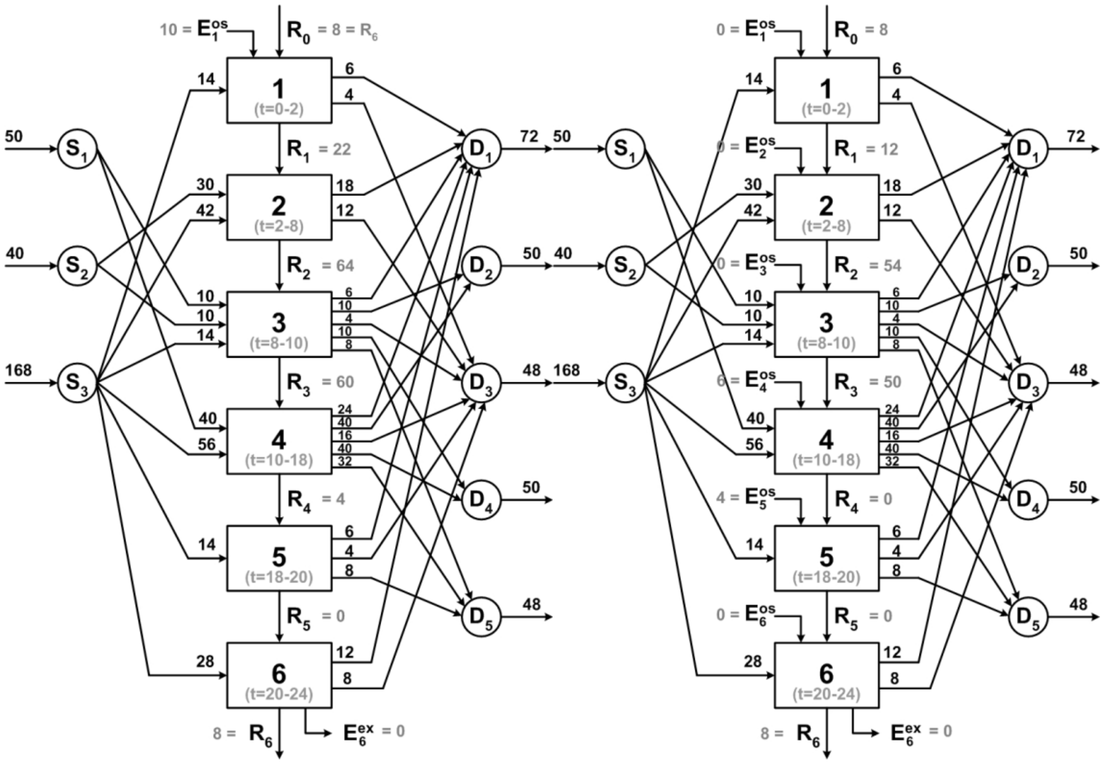
Power demand	Time (h)			Power rating generated	Electricity generation
	from	to	interval	(kW)	(kWh)
Appliance 1	0	24	24	3	72
Appliance 2	8	18	10	5	50
Appliance 3	0	24	24	2	48
Appliance 4	8	18	10	5	50
Appliance 5	8	20	12	4	48



(a)



(b)



(c) (d)

Figure 2: The results of CTM: (a) start up operation, outsourcing at beginning; (b) start up operation, outsourcing on demand; (c) normal operation, outsourcing at beginning; (d) normal operation, outsourcing on demand

5. Conclusions

The condensed/expanded transshipment models are proposed for analysis and design of the hybrid power systems. The problem of targeting the outsourcing electricity from the public grid, as well as the match of power supplies/demands are formulated as linear programming (LP) models. Numerical examples are supplied for demonstrating the proposed LP models for hybrid power targeting and design under various operating scenarios. Further studies will be investigated considering the possibility of storage loss for the surplus electricity.

Nomenclature

Indices:

i	index for power supply
j	index for power demand

Sets:

I	*i*| power supply *i* supplies electricity
J	*j*| power demand *j* demands electricity
K	1, 2,… ,K
K^0	0, 1, 2,… ,K
K^-	2, 3,… ,K
K^+	1, 2,… ,K-1

Parameters:

E_{ik}^{sp}	{*i*| electricity of power supply *i* in interval *k*

E_{jk}^{de}	j| electricity of power demand j in interval k
r	loss ratio from storage, $\approx$ 0.6 ~ 0.9

Positive variable:

E_{ijk}	PE: power supply i to power demand j at interval k
E_{k}^{imp}	Import electricity from public grid at interval k
E_{ik}^{sav}	PE: available plus power supply i exiting interval k
E_{k}^{sav}	PE: available plus power supply exiting interval k
E_{ik}^{use}	PE: reuse power supply i exiting interval k
E_{k}^{use}	PE: reuse power supply exiting interval k
E_{jk}^{imp}	PE: outsourced electricity to power demand j at interval k
$E_{k}^{\exp}$	Export electricity to public grid at interval k
$E_{ik}^{\exp}$	PE: power supply i to excess electricity at interval k
R_{ik}	PE: power supply i exiting interval k
R_{k}	power residual exiting interval k
S_{ik}	PE: available power supply i exiting interval k
S_{k}	power residual exiting interval k or PE: available power supply exiting interval k

Binary variables:

$y_k = 1$	Excess power for storage at interval k
$y_{ik} = 1$	Excess power from supply i to be stored at interval k

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