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Driver Selection in Utility System Design

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Utility system design deals with steam and power generation, distribution and utilization, and mechanical driver selection. Process machines such as compressors and pumps would be driven by electricity, steam turbines, and gas turbines, etc. Driver selection allocates a driving option to each shaft demand, along with the driver size and load.
System availability is an important issue in the system design. System availability can be improved by the equipment choice and its connection into the most appropriate configuration. However, higher system availability normally is achieved with high system costs.
Including driver selection into utility system design with availability estimation is a complex integration problem. This work has presented a methodology for the utility system design. A four-step decomposition methodology is proposed to achieve an optimized system configuration, equipment sizes, driver selection, and system availability assessment at the design stage.

1. Introduction

A utility system is designed to satisfy process heating, cooling, mechanical power, and electricity requirements (Sun, et al.,2014). The main considerations in the design contain fule consumption, steam generation and istribution, shaft power and electricity generation, and driver selection. System availability is an important issue in the design to guarantee system operation stability and safety.
Process mechanical machines such as compressors, fans, blowers and pumps, might be driven by electric motors, steam turbines and gas turbines. Driver selection allocates a driving option to each shaft demand, along with the driver size and load.
Considerable researches have been carried out on utility system design that excludes driver selection. For example, Mohammad et al. (2012) proposed coogeneration targeting procedure for total site. Razib et al. (2012) introduced a work exchanger network synthesis methodology to model compressor and turbine operation. Sun et al. (2013) analyzed heat and power generation in the steam systems. Pouransari and Maréchal (2014) analyzed energy integration of large-scale industrial sites with target-compatible strategy.
The methodology of driver selection integration with utility system design would cause more practical results. Del Nogal (2010) identified suitable equipment to accommodate more realistic utility system design. However, some practical considerations such as electricity import and export cost were not included in their approach.
Equipment failures in the utility system would lead to reduction of power and energy generation, system unstable operation, and even operation accident. Thus, system availability and reliability assessment is critical at the design stage (David and Smith, 2011). Methodologies for system availability and reliability evaluation have been developed (Frangopoulos et al., 2004), and been applied in many fields such as risk management and process control (Pittiglio, et al. 2014), etc. To incorporate the equipment failures analysis with utility system design, penalty costs (Aguilar et al., 2008), downtime penalties (Smith et al., 2011) have been proposed as the system reliability index in utility system optimization. Other reliability considerations have been addressed by the production cost using state probabilities as the weights for each possible operating state (El-Nashar, 2008). Sun and Liu (2015) analyzed reliable and flexible steam and power system without

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driver selection. These studies could all be extended by if there is additionally system availability assessment and estimation in the system design.
This work developes a methodology to optimize system power and steam generation, steam distribution, and driver selection, with system availability assessment at the design stage.

2. Driver selection integration with utility system design

Driver selection criteria are addressed firstly, and then the interaction among energy and power generation, driver selection, and system availability are analyzed. The utility system is designed based on a four-step decomposition approach.

2.1 Driver selection criteria

Driver options include electric motors, helper motors or generators, steam turbines, gas turbines, turboexpanders, and internal combustion engines. In general, there are three driver selection criteria:
1) Process requirements
Power and electricity demands by process rotational machines, driver available rotational speed, etc. are the basis of driver selection.
2) Economic analysis
Operating performance of driver options in terms of power and steam generation, efficiency, is determined by the component type, size, and operating load. For example, normally, the efficiency of a small sized turbine is lower than a large sized turbine.
3) Availability estimation
System availability is determined by the equipment selection (boiler, steam turbine, gas turbine, and condensing turbine), and their connection into the system configuration. More redundant equipment in the system can achieve higher system availability and reliability with high system costs and complex operation as penalty.

2.2 Driver selection within utility system design

As shown in Figure 1, driver selection would be integrated with utility system design with availability assessment.
The system design is to address the system configuration, including equipment selection of boilers (B), gas turbines (GT) with heat recovery for steam generation (HRSG), back-pressure steam turbines (ST), condensing turbines (CT), other auxiliary units, and driver selection. It is an optimization with the aim to achieve the minimum system costs. System availability ia assessed to obtain a reliable system design.

2.3Four-step decomposition approach

In general,there are four steps to achieve an optimal design:

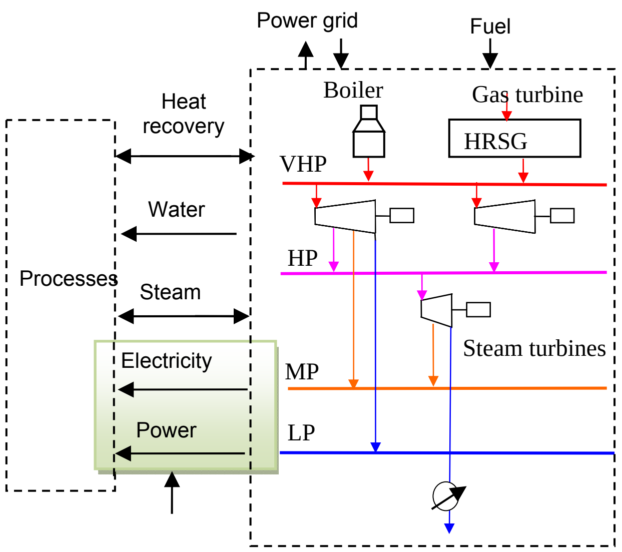


Figure 1: Utility system superstructure

Step 1 System components analysis
Process shaft power, electricity, and steam demands are the basis of the system design.
Step 2 Superstructure construction and decomposition approach
The utility system superstructure embeds all potential and feasible system components. To reduce the complexity of the optimization, superstructure- based decomposition approach is proposed. From the view of the driving source, the system is decomposed into non-steam driving subsystem and steam driving subsystem. As shown in Figure 2, gas turbines, electric motors, and power plants are driver options in the non-steam driving. This subsystem design mainly focuses on power and electricity generation. In the steam driving subsystem, the drivers might be steam turbine and electricity. Its design includes steam generation by boilers, gas turbines with HRSGs, and steam distribution by steam turbines and letdown valves.
Step 3 Mathematical models formulation and solution
A mixed integer linear programming (MILP) model is formulated with the objective of the minimum system costs. Fuel cost, water cost (raw water, make-up, pumping and chemicals costs), electricity cost or revenue, and emission charges or credits are included in the objective. In the optimization model, equipment types, sizes, and numbers are equipment decision variables. Boilers, steam turbines, and HRSGs are custom designed, and their sizes are continuous variables. Gas turbines have standard models with discrete size variables. Operational parameters include equipment operating loads, boiler feed water (BFW) cost, and electricity import or export cost. The selection of alternative components in the system and driver selection is expressed by binary discrete variable.
Equality constraints and non-equivalent constraints can not be violated in the optimization. Equality constraints are composed of mass balance, heat balance, electricity and shaft power balance. Equipment performance models and capital cost estimation models are also equality constraints (Shang et al., 2004; Aguilar et al. 2005). Non-equivalent constraints account for equipment size limits, available electricity import, and electricity export permission.
The model is solved by the software 'STAR' (CPI, UoM) developed by Centre for Process Integration, the University of Manchester.
Step 4 Solution analysis
Normally, system availability is a trade-off with system economy performance.
The system availability is contributed by system configuration and individual component availability. Individual component availability is calculated based on the component intrinsic failure distribution and repair time distribution (Ebeling, 1997), shown in Eq(1). The system availability A_s is estimated according to the Product Rule (Ebeling, 1997). For different system configurations in Figure 3 and Figure 4, the system availability is calculated based on Eq(2) to Eq(3).
For example, a system with components presented in Table 1, its availability is 0.8241. Its calculation is illustrated in Eq(4).

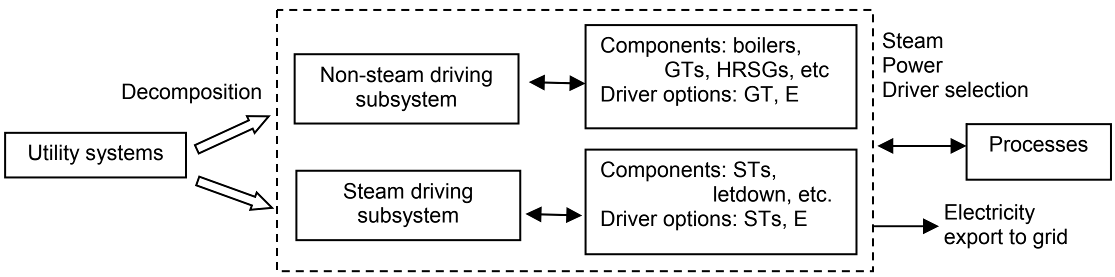


Figure 2: The superstructure of subsystems

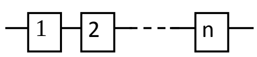


Figure 3: The system in serial

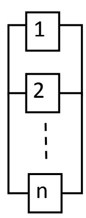


Figure 4: The system in parallel

Table 1: System component availability

Equipment		Numbers	Availability
Gas turbine	S206FA	4	0.9786
	GUD1-U94-2	2	0.9786
Electricity generator		6	0.9961
Steam turbine		4	0.9900

$$Availability\ (A) = \frac{uptime}{uptime + downtime} \tag{1}$$

The system in serial: $A_s = \prod_{i=1}^{n} A_i$ (2)

The system in parallel:

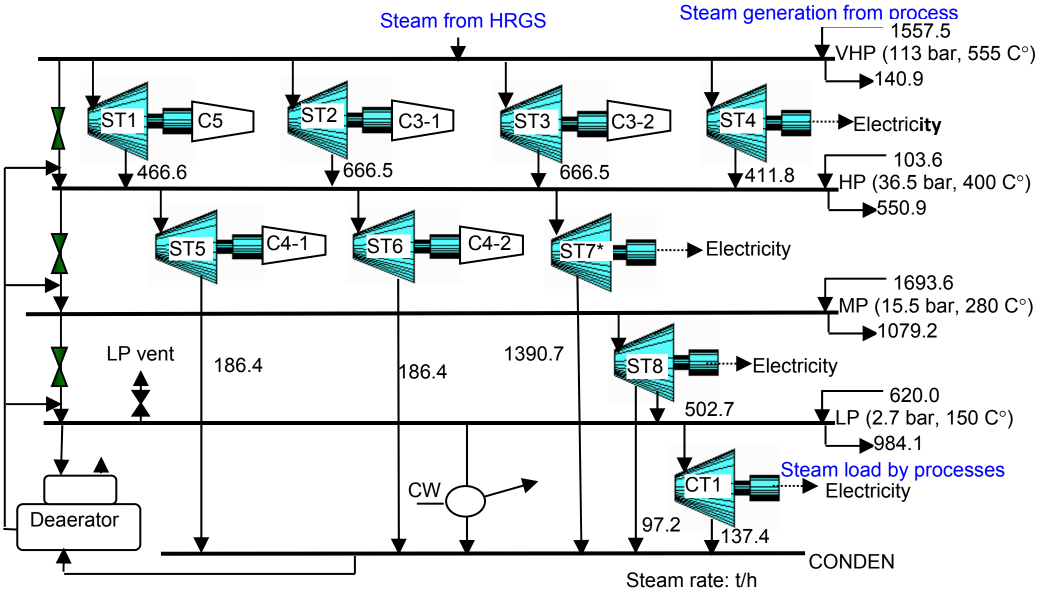
$$A_s = \frac{\prod_{i=1}^{n} A_i}{\prod_{i=1}^{n} A_i + \sum_{j=1}^{N} (1 - A_i) \prod_{j=1, j \neq i}^{n} A_j} \tag{3}$$

$A_s = 0.9786^4 * 0.9786^2 * 0.9961^6 * 0.9900^4 = 0.8241$ (4)

3. Case study

A utility system is designed to satisfy process mechanical, electric, heating and cooling demands. Process steam demands and steam generation from process heat recovery are illustrated in the system configuration in Figure 5. Process shaft power and electricity demands, and driver options are listed in Table 2.

Process tail gas (170 t/h) is the utility fuel in this design. Its net heating value is 27,000 kJ·(kg·K)$^{-1}$. There are 37 standard powerhouse turbines and 13 standard driver gas turbines candidates (Del Nogal, 2006) in the optimization. Steam turbines are custom designed. Both gas turbines and steam turbines are designed operating at their full loads. Table 3 presents design data.



* 6 same sized steam turbines operating in parallel

Figure 5: Steam driving sub-system

Table 2: Process power demands and driving options

Equipment	Symbol	Power MW	Numbers	Driving options
Compressor	C1	55.0	4	ST /GT /E
Compressor	C2	41.0	1	ST /GT /E
Compressor	C3	50.0	2	ST /GT /E
Compressor	C4	43.0	2	ST /GT /E
Compressor	C5	35.0	1	ST /GT /E
Others site demand		100		E
Total		582		

Table 3: Design data

Driver shaft		Costs	
Min startup load fraction	0.05	Power cost/ £·kWh^{-1}	0.068
Max motor/generator load fraction	0.25	Power value/ £·kWh^{-1}	0.05
Helper motor efficiency	0.95	Carbon emission tax/ £·t^{-1}	40
Helper generator efficiency	0.95	Cooling water cost/ £·kWh^{-1}	0.0125
Electric motor efficiency	0.95	Demineralised water cost/ £·kWh^{-1}	0.0125
Electricity distribution loss	0.02		
transmission loss	0.015		

3.1 Design options

Steam turbines (ST), gas turbines (GT), and electricity (E) are driver options. Following the proposed methodology, four scenarios are proposed and optimized: Scenario 1 (S1) is the electricity driving design. Scenario 2 (S2) is the steam-driving design. In this option, STs and E are driver options. Scenario 3 (S3) is non-steam driving design. GTs and E are driver options. in this design. Scenario 4 (S4) is the mixed driving design. GTs, STs, and E are driver options.

Because the fuel in the system is fixed, the system is optimized mainly focused on electricity export, the capital costs, and system availability estimation with driver selection. We consider here an example with S4 optimization. There are 115 continues variables, 23 discrete variables, and 161 constraints in the steam driving subsystem optimization. 519 variables and 331 constraints are involved in the non-steam driving subsystem design. Figure 6 shows the optimal steam driving subsystem configuration of S4. Note, ST7 in Figure 6 is not a single steam turbine due to the limits of equipment sizes. There are 6 same sized steam turbines operating in parallel.

Table 4 compares equipment selection, driver selection, electricity export, the capital cost, and the system availability of the four optimized scenarios.

Table 4: Four design comparisons

	Non-steam driving subsystem Standard GTs	Steam driving subsystem Number of STs	Driver selection*	Electricity export MW	Capital cost M$	Availability
S1	Industrial GT: PG7121EA, PG9171E, W501G	13	Electricity	509.1	193.5	0.7962
S2	Industrial GT: PG7121EA, PG9171E,W501G	15	C1- C5 by STs	518.9	193.7	0.7804
S3	Driver GT: 10×LM6000; Houseplant GT: PG5371, PG6581	13	C1- C5 by Driver GTs	563.1	269.0	0.6576
S4	Driver GT: 5×LM6000; Houseplant GT: PG9231EC, PG7121EA	14	C1-C2 by Driver GTs C3-C5 by STs	530.1	220.8	0.7396

*****Others site demands are driven by electricity

From Table 4, it is clear that the system economy and reliability are traded-off in the utility system design with driver selection. S3 with gas turbines and electricity as drivers can export the maximum electricity to the grid as the profit. However, its capital investment is the most expensive among these design scenarios. S1 based on electricity driving is the most reliable design, but, its electricity export is the minimum.
The optimal decision is finally based on decision makers' preferences.

4. Conclusions

This work has proposed a methodology to optimize utility systems to achieve more realistic system configuration with driver selection and availability assessment. The system availability has the same priority as the economic objective in the design. In this work, system availability is estimated based on equipment full load operation and full production scale without redundancy. The system availability would be different for a system with redundant equipment and equipment in part load operation.

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