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Shore to Ship Power for Mombasa Port Possibilities and Challenges

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***Abstract*—** Control of air pollution from docked ships is one challenge that ports encounter in their effort to reduce operational environmental impact. Ship-to-shore power has been identified as one technology to reduce emissions by at least 90% in harbour areas as given by International Convention for the Prevention of Pollution from Ships (MARPOL). As an international best practice of a green port, installation of shore power technology for Port of Mombasa should be considered. To implement shore power technology, a detailed analysis of existing power system should be done to determine the effect of the topology of the connection and the effect the system will have on the stability of the grid.

This paper develops an aggregate load model in MATLAB of electrical ship loads to be applied in carrying out the analysis of the impact of connecting shore power at Mombasa on the voltage stability of the on shore grid. An induction motor model is developed by aggregation of induction motor loads. Lighting and other non-motor loads are represented as a constant power static model. The model parameters are developed using a component based approach, whereby data is collected from shipping lines for ships docking in Mombasa port. The starting characteristics is analysed and found to be consistent with the expected load characteristics of a mainly inductive motor load. The paper concludes that the existing shore-side supply has the capacity to take up the full load of a ship, including direct on line starting of on-board motors.

The results will be used for a load flow study to determine the effect of such an installation on the voltage stability of the on shore grid.

***Keywords*—**Load Modelling, Aggregation, Shore-to-Ship, Stability

I. INTRODUCTION

The progress of economic globalization, the rapid growth of international trade and maritime operation have played an increasingly significant role in providing international cargo and passenger transportation. Consequently, seaports all over the world are suffering from the problem of fuel consumption and exhaust gases coming from ships during their stopover in harbors. The electricity generated on board is used to provide power for a wide range of applications like lighting, cooling, ventilation, pumps, navigation systems, cargo loading and offloading activities. At berth the main engine is switched off and the auxiliary generators take control of all the power generation on board. Different ships will have different on board power demands. This continued expansion of global trade has drawn the attention of several regulatory parties including International Maritime Organization (IMO), International Convention for the Prevention of Pollution from Ships (MARPOL) and European Union (EU) where strict environmental legislation have been enacted forcing the shipping industry to look for ways and means to reduce this negative environmental impact. Pollution from maritime shipping in ports and harbours are largely dominated by the presence of Particulate Matter (PM), Sulphur Oxides (SO_x), Nitrogen Oxides (NO_x), and Carbon Dioxide (CO_2) [1], [2]. According to a SISTI study (Italian Study on Susceptibility to Temperature and Air Pollution) these pollutants have adverse effect on human health and at a global level, CO_2 is the most significant contributor to global climate change [2].

Berthed ships can either generate their own electricity using clean fuel, or connect to utility power sockets at the port. Research so far done has shown that the latter is the most sustainable solution, in every way [3], [4]. This arrangement reduces local emissions and vibrations at the port. In cases where the grid electricity is derived from green sources, global emissions are also reduced. It also provides the port with additional sources of revenue from selling shore power to ships. The benefits to shipping lines include lower costs for fuel and maintenance and achieving green status.

Earlier shore power connections used low voltage connections but the current trend is to use medium voltage (6.6kV or 11kV) in order to cater for the largest ships and reduce the number of cables used in connections. To meet the demand for shore to ship connections, manufacturers such as ABB, Cavotec, Siemens and Schneider Electric have developed their systems for implementation of shore power connections. EU recommendations 2006/339/EC specifies typical shore side power connections that may be applied. Also, the Institution of Electrical and Electronic Engineers (IEEE), International Electrotechnical Commission (IEC) and ISO have developed an international standard (IEC_ISO_IEEE 80005-1 Ed1) which specifies [5]:

- HV-shore supply requirements
- Shore side installation

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- Ship-to-shore connection and interface equipment, plugs and sockets
- Ship requirements
- High Voltage Ship Connection (HVSC) system and control monitoring
- Verification and testing
- Periodic tests and Maintenance

A standard for low voltage connections (IEC 80005-3) is under preparation.

According to the World Ports Climate Initiative (WPCI), currently there are 22 ports in Europe and North America that have applied shore power supply in their electrical infrastructure and they have experienced significant environmental improvement [6]. The organization also lists an additional 28 ports in Europe, North America and Asia that have ongoing plans to install on shore power connection.

In Kenya, more than 70% of the electricity supplied to the national grid is generated from green sources such as geothermal and hydro [7]. Use of shore to ship connection for the port of Mombasa would therefore result in a major reduction in the environmental footprint of ships that use the port. Viability of such a scheme will depend on of the technical, financial and environmental factors involved in the implementation.

Currently, Mombasa Port maximum demand is at 4MW according to February 2016 power bill. The peak demand for a berthed ship can range from 170KW for a small container vessel to 12000KW for large tankers and cruise ships. The main factors that would affect the technical viability of a shore to ship power supply are therefore the ability of the shore-side supply to meet the demand of the on ship consumption at berth and the effect of the interconnection on the stability of the on shore grid.

This study seeks to develop a model for the electrical load for the typical ships that can dock at the port of Mombasa. The model will be applied in later investigations that will include a load flow study to determine the voltage stability for a ship to shore installation at the port of Mombasa.

II. PREVIOUS WORK

A. Power System Load Modelling

The study of load flow and dynamic behaviour in power systems requires a modelling of the connected load. Models used include constant power (PQ), polynomial model (ZIP), exponential recovery, induction motor and composite models [8], [9]. Whichever model is selected, an estimation of model parameters is required. According to a worldwide survey of electric power transmission companies [9], the most common approaches to load modelling are constant power model for steady state analysis and a composite model for short term voltage stability. The survey identified measurement based methods as the most common approach for estimation of model parameters. Use of standard models in the literature, such as that provided in [8] is the second most common approach to parameter estimation.

Alternative approaches of parameter estimation have been proposed in order to get more accurate representation of the loads or where measurement is not feasible. Approaches that take into account the separate components that make up the total load have been proposed in [10] and [11].

In this paper propose to develop a model to study short term voltage disturbance. It is therefore proposed to use a composite model that includes one or more induction motor models developed through motor aggregation and a static constant power load to represent non-motor loads. Parameters for the model are derived from data equivalent manufacturer data for specific load types.

B. Ship to Shore Power Installations

Previous studies on shore to ship power connection have looked at the expected loads and connection time as well as the requirements for voltage and frequency. Radu et al [2] studied the ship berthing patterns at European ports. They found that the loads range from 300KVA to 20MVA while berthing times range from 3 hours to 80 hours. These factors depend on the nature of the ship and berthing time. The high power consumption will require very large cables if the connection is based on a low voltage system. It is therefore recommended that the supply be at medium voltage (6.6kV) with an on-ship transformer to convert to rated low voltage of on board supply. Borkowski and Tarnapowicz [12] have presented a study of a ship that was undergoing conversion to use on-shore power. Although their focus is on emissions, it is noted in the paper that the conversion included an on board transformer.

In both [1] and [2], it is established that berthing ships have voltage and frequency ranging from 400V 50Vz to 480V 60Hz. 60Hz was found to be the predominant supply frequency except in small container vessels where 50Hz is the predominant frequency . It is therefore recommended that shore to ship installations in countries with 50Hz grids include an on-shore 50Hz – 60Hz frequency converter and HV/LV transformers in order to supply 60Hz vessels. A typical solution by Schneider consists of a 2MVA or 3MVA unit packaged in a container with detailed safety requirement [13].

Ion et al [14] have carried out transient analysis of a shore to ship connection, with focus on the operation of the frequency converter. In the study, the ship load is modelled as an induction motor and aggregation techniques are used to combine the ship into one load. None motor loads like lighting and cooking range are ignored.

In this study motor loads will be aggregated and represented as one or two induction motor loads. A study of the interconnection systems such as transformers, frequency converters and cables will not be carried. This will be included in the next stage where a load flow study is proposed.

C. Induction Motor Aggregation

A simulation of a load consisting of a large number of induction motors can be computationally expensive. The solution is to aggregate the motors into one equivalent motor to ease the computation. The equivalent circuit approach has been proposed by Pillay and Sabur in [15]. Further work has been done by Kataaoka et al [16] and Karakas et al [17]. Measurement based have been proposed in [18] and [19]. Aree [20] has proposed a different approach using energy conservation law.

On the criteria for grouping motors together for aggregation, Pillay and Sabur [15] propose that motors should be grouped together based on their impedance relationship. Ion et al have proposed to group together all motors connected to one bus.

The equivalent circuit of an induction motor is shown in Fig 1. The equivalent circuit approach aggregates the equivalent inductance and resistances to achieve an aggregated inductance and resistance model [17].

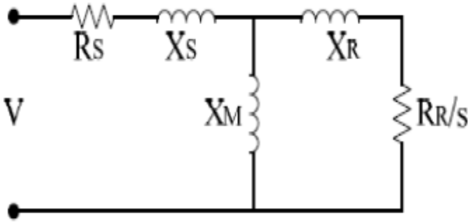

Figure 1: Equivalent circuit of induction motor

This paper uses the aggregation method for no load condition and locked rotor condition proposed in [17]. Motors will be grouped together based on their load torque characteristics.

III. AGGREGATION OF CONTAINER SHIP LOADS

A. Total Electrical Load for Ship

The total loads in the container ship Kota Hapas 29 are given in Appendix A.

A simulation of these loads is required in order to study the effect of interconnection of the ship to on-shore grid. The number of individual loads on the ship are too high and it would not be efficient to simulate them individually. Aggregation of loads is carried out in order to simplify the simulation. In this case, the loads will be grouped for simulation as highlighted by the cell background colours in Table I. This is based on:

1. Blue for motor loads with a load torque characteristic where torque is proportional to square of speed (fans and pumps).
2. Green for motor loads with a load torque characteristic where torque is almost zero at starting speed and constant at higher speeds (compressors, hoists).
3. Red for purely resistive or inductive loads without a substantial starting current.
4. Yellow for loads that are not part of the ship and may not be always present (refrigeration containers).

Equivalent circuit parameters for installed electric motors are obtained from manufacturers' data or estimated using IEEE recommendations [8]. Motor loads are aggregated using the no load and locked rotor equivalent circuit models.

Motors with torque characteristic of fans and pumps are aggregated together to produce one aggregated motor load.

A second aggregated motor load is developed by aggregation of hoist (cranes) and compressor motors.

Resistive and inductive loads are added together and simulated as one R-L load.

B. Aggregated Load Parameters

A Matlab script has been applied to implement the aggregation equations and evaluate the parameters required to simulate an asynchronous motor in Simulink.

The resultant aggregated motor parameters for fan and hoist motors are given in Table I.

TABLE I

AGGREGATED PARAMETERS FOR MOTORS

Parameter	Fan Motors	Hoist Motors
Rated Power (VA)	4.8370E+05	4.7000E+05
Rated Voltage (RMS) (V)	4.0000E+02	4.0000E+02
Rated Frequency (Hz)	5.0000E+01	5.0000E+01
Stator Resistance (Ω)	3.1297E-02	3.7777E-02
Stator Inductance (H)	2.5700E-05	3.4995E-05
Rotor Resistance (Ω)	1.3635E-02	2.4814E-02
Rotor Inductance (H)	3.8550E-05	3.4995E-05
Mutual Inductance (H)	1.7756E-03	2.4801E-03
Moment of Inertia (Kg.m^2)	2.6610E+01	1.8551E+01
Friction Factor (N.m.s)	1.0158E-01	9.7095E-02
Number of Pole pairs	2.0000E+00	2.0000E+00

C. Non-Motor Loads

Non-motor loads consist of the cooking range and lighting. Lighting is composed of high power factor discharged lighting, with a power factor of above 0.8. The cooking range load is composed of hot plates and ovens (induction and resistive, with a power factor close to 1) and accessories such as dish washers. The total non-motor load will be modelled as an inductive load with a high power factor of 0.9. This is summarised in Table II.

TABLE II

NON-MOTOR LOADS

Description of load	Cooking range	Lightings(all)	TOTAL
Quantity	4.00	1.00	
KW	25.00	22.86	
Total KW	100.00	22.86	122.86
PF	0.90	0.90	
Total KVA	111.11	25.40	
Total KVAR	48.43	11.07	59.50

D. Aggregated Model

The aggregated load is modelled Simulink/MATLAB as shown in Appendix B. This will enable to the model to be tested in order to confirm that it meets the expected characteristics of the simulated load. The model consists of the following components:

1. A 3 MVA, 415V 3 phase source to supply power for the test. The rating of the power supply because this power rating is one that is commercially available and has a capacity that can be accommodated within the existing installation at the Mombasa Port.
2. A damping resistor, which is required in Simulink when a power supply is connecting to an inductive load.
3. Two asynchronous machine models to represent the aggregated motor loads. These have the following inputs and outputs:
    a. Motor parameters in Table I are input as settings for the asynchronous machines.
    b. A model for load torque. This is set as a function of speed as described in Section E below.
    c. Operational measurements used are rotor speed and electromagnetic torque output.
4. An RL load with settings as given in Table II to represent non-motor loads.
5. Circuit breakers which are set to open or close as required for the simulation.
6. Current, voltage and power measurement blocks.
7. Oscilloscopes to display and save measured variables.

E. Load Torque Model

Simulation of motor loads also requires a model of load torque. The models used are:

1. Load torque is proportional to speed for fans and pumps. This is modelled as:

$$T_m = k\omega_r^{\,2} \qquad (1)$$

Where T_m=Mechanical torque, ω_r = rotor angular speed and constant $k = T_R/(\omega_R)^2$, where T_R is full load torque and ω_R is full load angular speed.

2. Constant torque (at higher speeds) for hoists and compressors. This is modelled as:

$$T_m = \begin{cases} k_1\left(\frac{\omega_R}{2}\right)^2 & \omega < {}^{\omega_R}\!/_2 \\ T_R & \omega \geq {}^{\omega_R}\!/_2 \end{cases} \qquad (2)$$

Where T_m=Mechanical torque, ω_r = rotor angular speed, ω_R = rotor angular speed at full load and constant, $k_1 = T_R/(\omega_R/2)^2$, where T_R is full load torque. The build-up of the load torque as motor gains speed after starting is demonstrated in Fig 2.

IV. TEST RESULTS

A. Motor Starting

In a normal shore to ship operation the transfer of load from on board supply to shore supply is done by synchronising on board generators with the shore side mains and switching off the generator when the two systems are synchronised. Once the load has been transferred to the shore side mains, it may be switched on or off depending on the requirements of the ship.

It is therefore necessary to test model for the following conditions:

1. Load is switched to mains supply from condition of motors being at zero speed and on no load. Test of this situation is carried out by arranging for the circuit breakers CB1, CB2 and CB3 to be closed and the shore-side CB is switched to closed position at the start of the test.
2. Once the motors have started and reached rated speed and torque, the circuit breakers CB1, CB2 and CB3 are opened for a very short time and then closed again.

The simulated tests were carried out and measurements of phase to neutral voltage, phase current, active and reactive power, rotor speed and electromagnetic torque taken.

The results are presented in Fig 3 to Fig. 9.The power disconnection event can be observed at 1.75 seconds.

It is observed that the aggregated motors demonstrate the characteristics that are expected for an induction motor at start for speed, torque, voltage current and power. It is also noted that the two motors have slightly different torque characteristics, as would be expected. The hoist motor has a more uniform torque, with maximum torque almost equal to full load torque.

The 3MVA supply is able to start the motors from standstill to near the calculated full load speed. When the supply suffers a short disturbance as would be expected during change-over from one source to another, the model demonstrate an ability to quickly recover and settle at the same operating conditions as were existing before the disturbance.

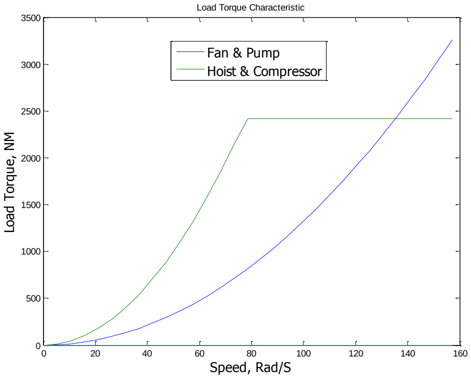

Figure 2: Load Torque Characteristics

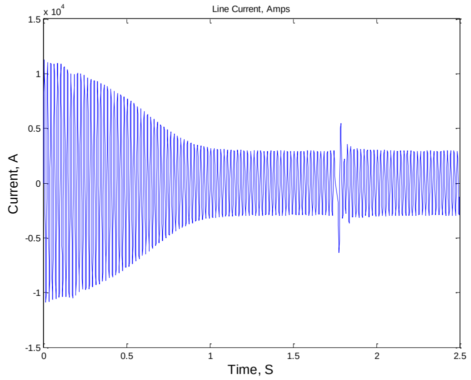

Figure 3: Total Line Current, Phase A

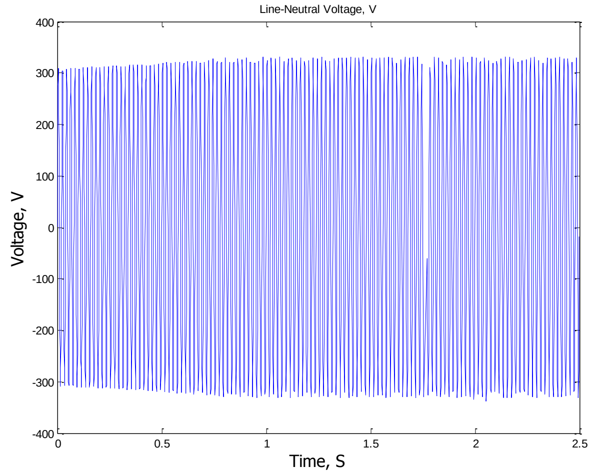

Figure 4: Line to Earth Voltage, Phase A

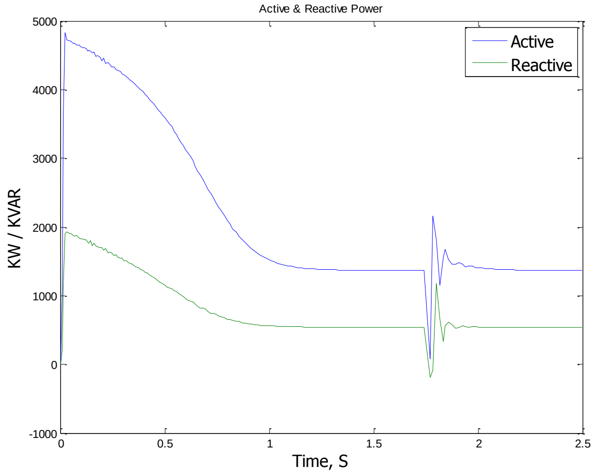

Figure 5: Total Power (Active & Reactive)

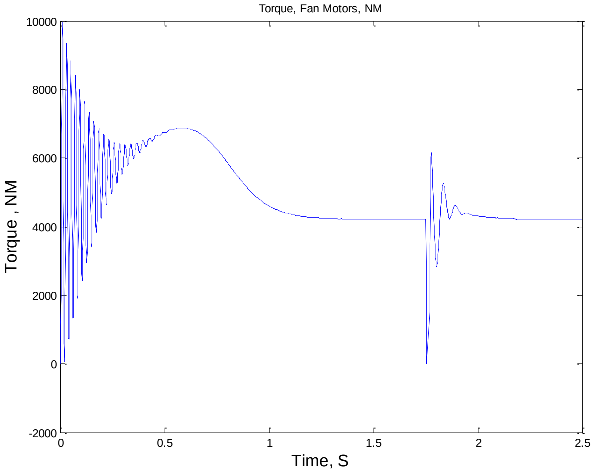

Figure 6: Electromagnetic Torque, Aggregated Fan & Pump Motor

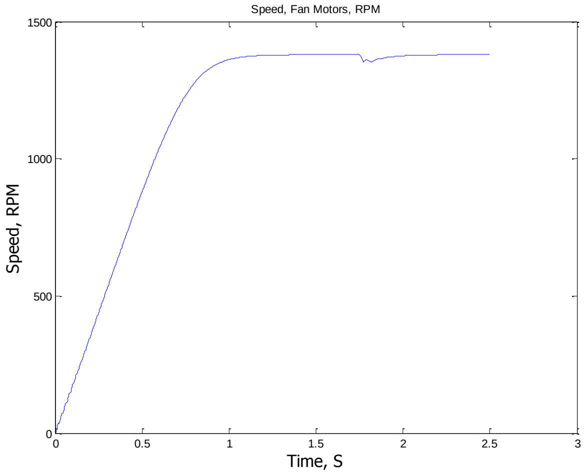

Figure 7: Rotor Speed, Aggregated Fan Motor

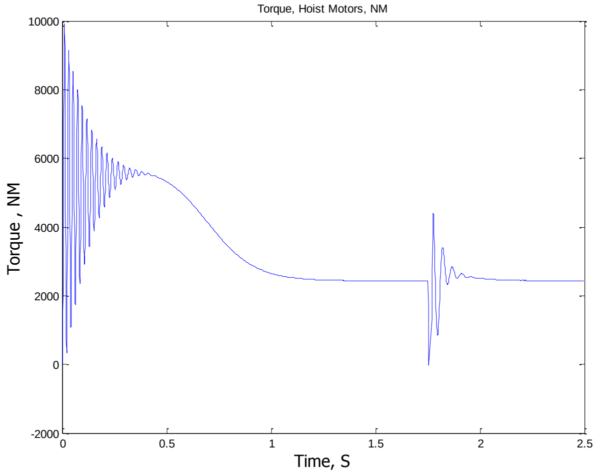

Figure 8: Electromagnetic Torque, Aggregated Hoist Motor

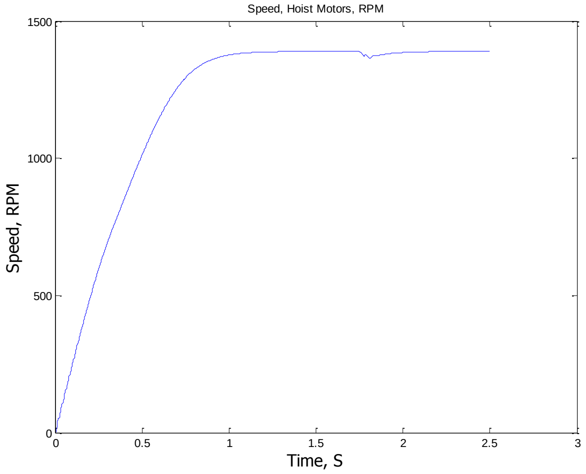

Figure 9: Rotor Speed, Aggregated Hoist Motor

B. Steady State Operations

In order to observe the steady state operating conditions of the container ship model, the simulation was carried out for steady state operation of the loads with starting parameters as calculated from the model by Matlab. The results are presented in Table III. The total power drawn from the 3MVA source is 1346KW, 545.8KVAR.

TABLE III

STEADY STATE PARAMETERS

Description of load	Voltage		Current	
	Magnitude (V)	Angle (Degrees)	Magnitude (A)	Angle (Degrees)
Total Ship	239.6	0.0	2,051.3	-23.5
Fans	236.1	28.6	920.9	-26.4
Cranes	236.1	28.6	932.1	-19.7
Lighting etc.	236.1	-1.4	201.9	92.6

V. CONCLUSION

A model for the electrical load on a ship has been developed and tested. The tests confirmed that model demonstrates the expected characteristics of an induction motor load.

It was also noted that a 3MVA supply is able to take up the load of more than 1000KW which includes direct on line motor starting. Steady state operating conditions for the container ship model were also derived. The steady state values will be applied as initial conditions when performing a load flow study. In order to achieve a complete model of a shore to ship supply for the Port of Mombasa, modelling of other types of ship and estimation of total number and types of ships to be connected is required. The complete model can then be used for a study of voltage stability.

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APPENDIX A

TABLE IV

ELECTRICAL LOADS ON KOTA-HAPAS 20 (SOURCE: KPA OPERATIONS DEPARTMENT)

Description of load	**Qty**	**KW**	**Total KW**	**Total HP**	**RsΩ**	**XsΩ**	**RrΩ**	**XrΩ**	**XmΩ**	**Jkgm2**	**Nr (RPM)**
Cooling sea w/pump	1	28.9	28.9	39	0.59	0.15	0.16	0.16	12.49	1.3	1470
C/fresh w/pump	1	12.4	12.4	17	1.38	0.29	0.18	0.18	23.57	0.57	1450
M/E lube oil	1	69.9	69.9	94	0.27	0.09	0.16	0.11	4.63	2.58	1484
Exhaust valve pump	1	4.4	4.4	6	4.02	1.46	2.05	2.05	69.73	0.19	1430
Fuel oil, boiler motor	2	2.8	5.6	8	3.45	1.2	1.63	1.63	59.77	0.26	1420
Fuel oil circ..pump	1	6.3	6.3	8	3.45	1.2	1.63	1.63	59.77	0.26	1435
Fuel oil trans.pump	1	8.5	8.5	11	2.61	0.82	1.01	1.01	44.82	0.36	1445
G/E sea w/pump	1	16.7	16.7	22	1.13	0.24	0.17	0.17	20.26	0.73	1465
G/E D.O supp.pump	1	3.8	3.8	5	4.3	1.59	2.26	2.26	74.72	0.16	1430
Ballast/pump	1	39.8	39.8	53	0.41	0.14	0.15	0.15	9.14	1.72	1480
Fire and GS	1	39.8	39.8	53	0.41	0.14	0.15	0.15	9.14	1.72	1480
Fire, ballast	1	86.4	86.4	116	0.23	0.07	0.14	0.09	3.66	3.24	1485
Air comp.	2	47.8	95.6	128	0.21	0.07	0.13	0.08	3.43	3.64	1483
Engine R/vent	2	57.8	115.6	155	0.17	0.05	0.09	0.07	2.91	5.55	1483
A/C plant	1	28.9	28.9	39	0.59	0.15	0.16	0.16	12.49	1.3	1470
A/C fan	1	16.7	16.7	22	1.13	0.24	0.17	0.17	20.26	0.73	1465
Cooking range	4	25	100	134							
Plant/comp.	1	4.4	4.4	6	4.02	1.46	2.05	2.05	69.73	0.19	1430
Cargo cranes	2	185	370	497	0.11	0.03	0.09	0.03	2.91	5.55	1487
Lightings(all)	1	22.86	22.86	31							
Refer containers	150	34.8	5220	7005	0.32	0.14	0.15	0.15	9.14	1.72	
TOTAL	177		6297	8449							

APPENDIX B

AGGREGATED MODEL

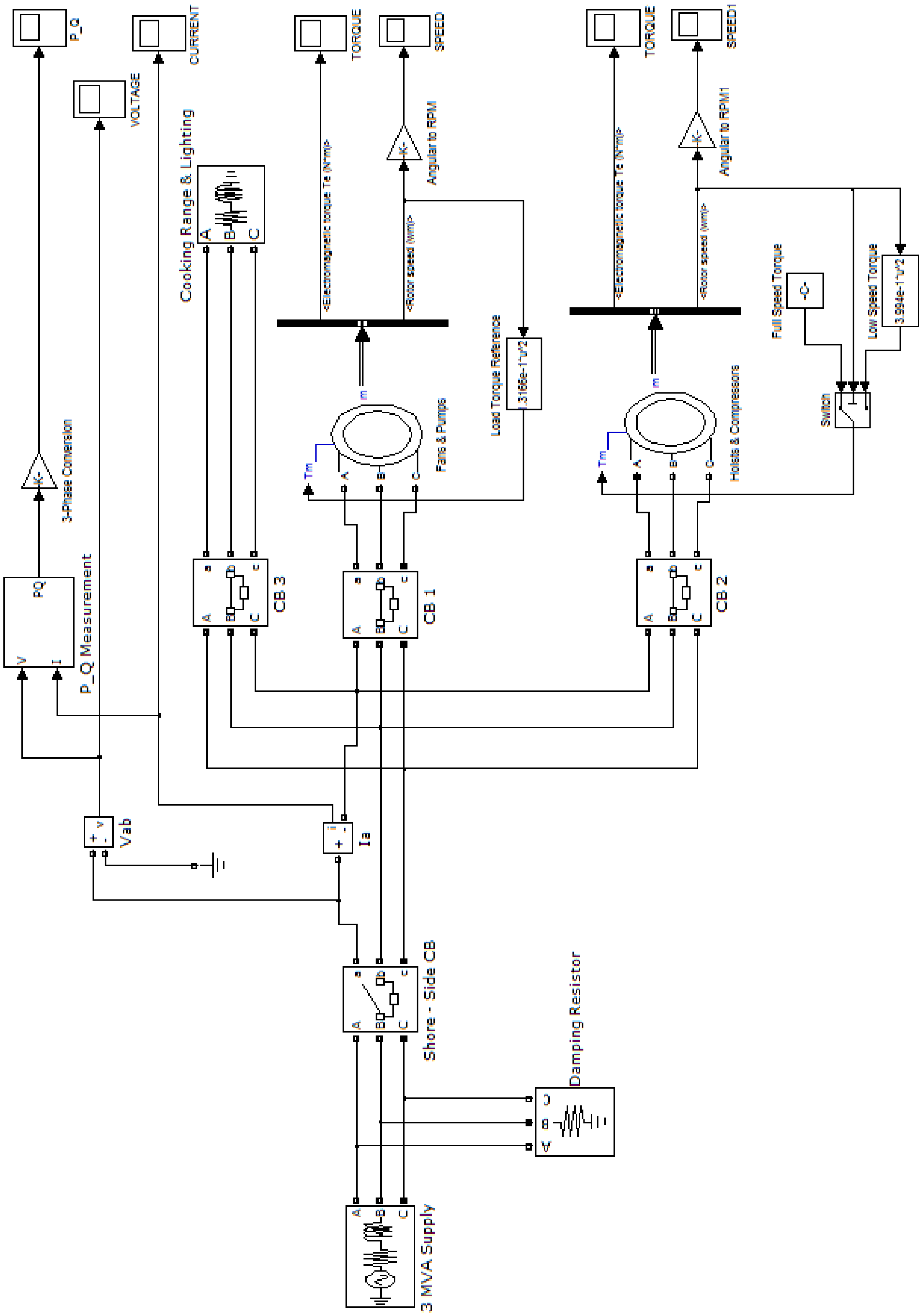

Figure 10: Simulink Model for Aggregated load on Kota Hapas 29