FEASIBILITY STUDY, DESIGN, DYNAMIC MODELLING, SIMULATION, AND CONTROL OF A SOLAR POWERED SUCKER ROD OIL PUMP

PhD Oral Defence

By

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Presentation Outline

- **Introduction**
  - Background and Motivation
  - Research Objectives

- **Sizing, Parametric Investigation and Analysis of Automated Sucker Rod Pump using Beam Pump Simulators :**
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  - Site Description
  - System Design Methodology and Parametric Investigation
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  - Site Description and Renewable energy potential of the selected location
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Presentation Outline

- **Open source IoT-based SCADA system for remote oil facilities using Node-RED and Arduino microcontrollers :**

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  - Web Interface and Node-RED IoT Platform on the Local Server
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Introduction - Background and Motivation

- Globally, conventional hydrocarbon resources are being steadily depleted, with a growing need for an artificial lift for production management [1].

- Deployment of artificial lift (gas or beam pumping) to extend the life of a producing well [2,3] is vital to maintain production at the desired level.

- At every phase during the life of a well, the need to minimize the cost of production, increase energy return on investment, improve pump volumetric efficiency, prolong pump life and improve overall production efficiency, cannot be overemphasized [4-7].

- Petroleum production continues to face the reality of price fluctuations, and hence low-budget operations are required [8,9].

- Oil wells are increasingly abandoned in Canada due to technical and economic limitations to production [10].

- The need for a simple, economical, and environmentally sustainable alternative to keep the oil and gas wells on-stream and minimize the impact of the depressive market cannot be overemphasized [1].

- Considering the prohibitive cost of premature oil well abandonment, this study develops innovative solutions to sustainably maintain production from low-flow rate idle or suspended oil wells.

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Introduction - Research Objectives

- This research develops an approach for estimating the energy requirement of a low flow rate oil well driven by a sucker rod pump.

- The pump’s energy requirement is then taken as a load driven by a 3-phase squirrel cage induction motor.

- Technical and economic analysis is performed to determine the most feasible rating of 100% renewable energy sources that can be sustainable deployed to drive the pump under intermittent and continuous pumping scenarios.

- A low cost, open source, internet of things supervisory control and data acquisition system is designed to ensure automated data acquisition, logging, monitoring and visualization of key performance indicators onsite.

- The least cost, 100% solar PV and battery storage powered microgrid, is designed to drive the sucker rod pump-powered oil well.

- This research provides a renewable, fully electrified micro-grid system that is integrated with a low-cost, open-source Internet-of-Things SCADA system.

- The design is to empower the operators to reduce the carbon footprint of low-flowrate oil wells and have full control of their onsite renewable energy generation.

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Design and Analysis of Sucker Rod Pump

Site Description

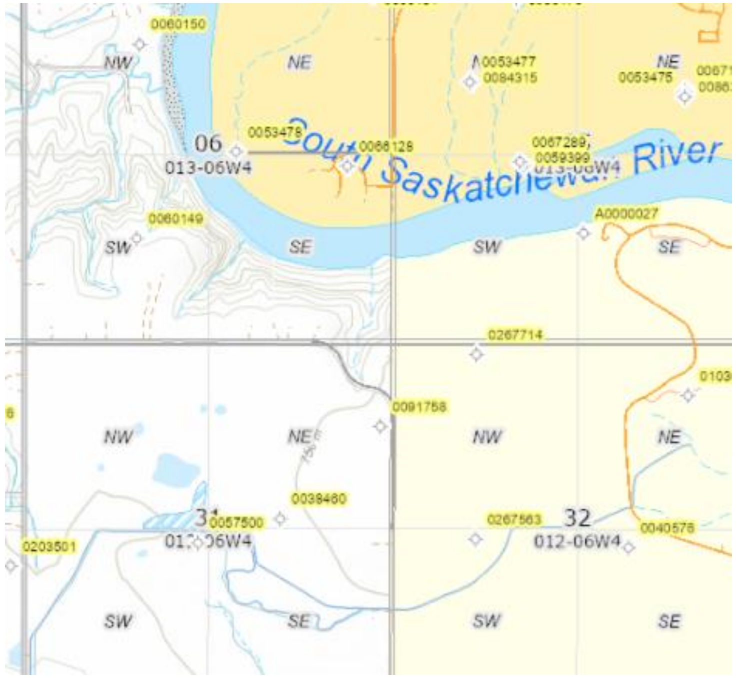

Fig 1 Remote wells in proposed site

Fig 2 Aerial view of the proposed site

The proposed site is near Medicine Hat, a city in southeast Alberta, latitude 50^{0}2’32” N and longitude 110^{0}48’49” W. Like most of the Prairies, there are abundant suspended, orphaned, and abandoned wells in this area, and the parameters used for this system design were obtained from an analogous site which serves as our case study for the simulator integration.

Design and Analysis of Sucker Rod Pump

System Design Methodology and Parametric Investigation

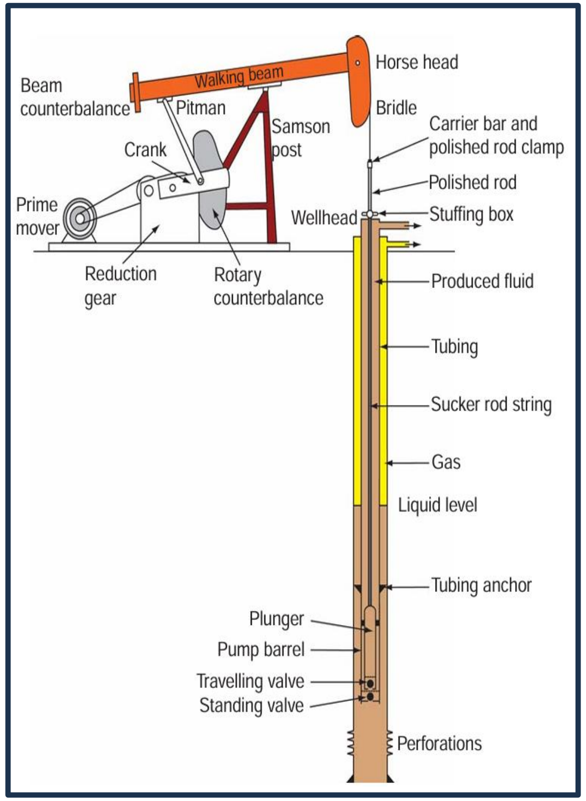

Fig 3 The sucker rod pumping system[11]

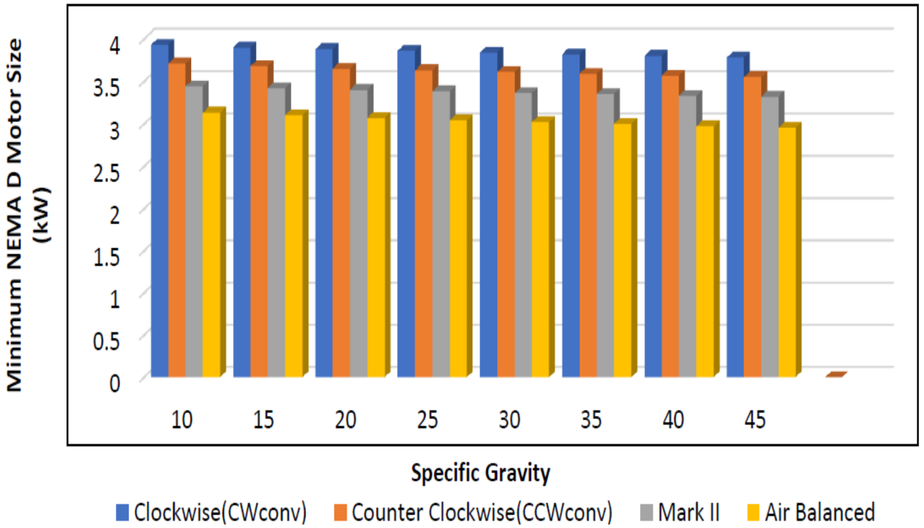

Fig 4 API gravity versus Energy requirement for different geometries

- There is a significant reduction in the energy requirement as one transitions from heavy oil (10^0) to lighter oil (45^0).
- Mark II pump minimizes the energy requirement and is more reliable than air-balanced.

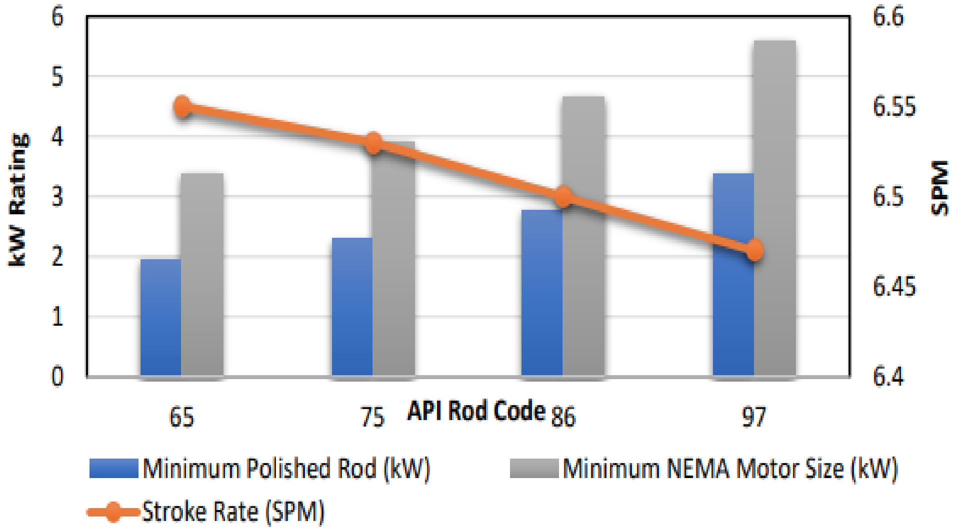

Fig 5 API rod number as a function of minimum polished rod size, stroke rate, and prime mover rating

- The energy requirement consistently increases with tapering for API rod numbers 65 to 97, validating the choice of API 65.
- API rod number 65 is selected to sustain a target level of production at a minimum motor rating.
- Rod 6 (0.75"), Rod 5 (0.625"), Rod 7 (0.875"), Rod 8 (1.0"), and Rod 9 (1.125").

Design and Analysis of Sucker Rod Pump
System Design Methodology and Parametric Investigation

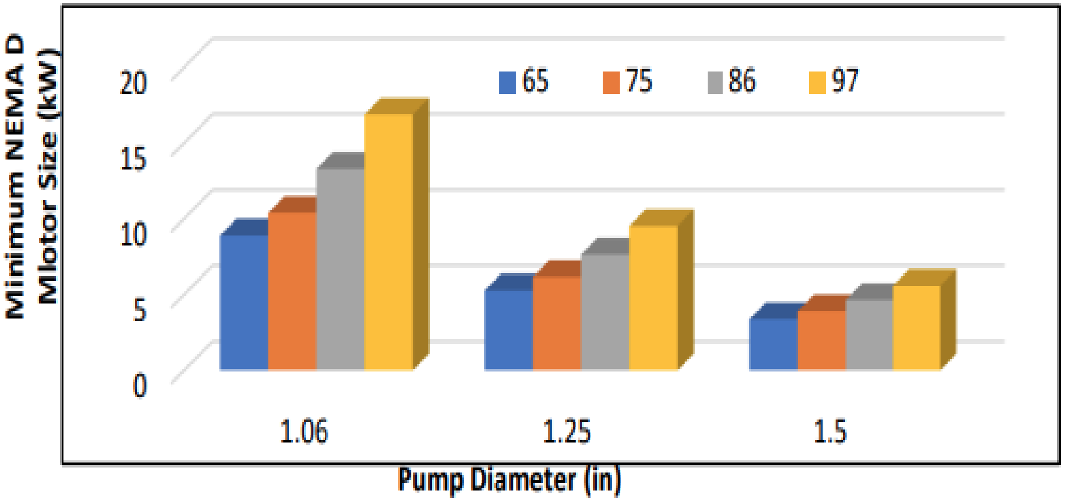

Fig 6 Prime mover rating by pump diameters

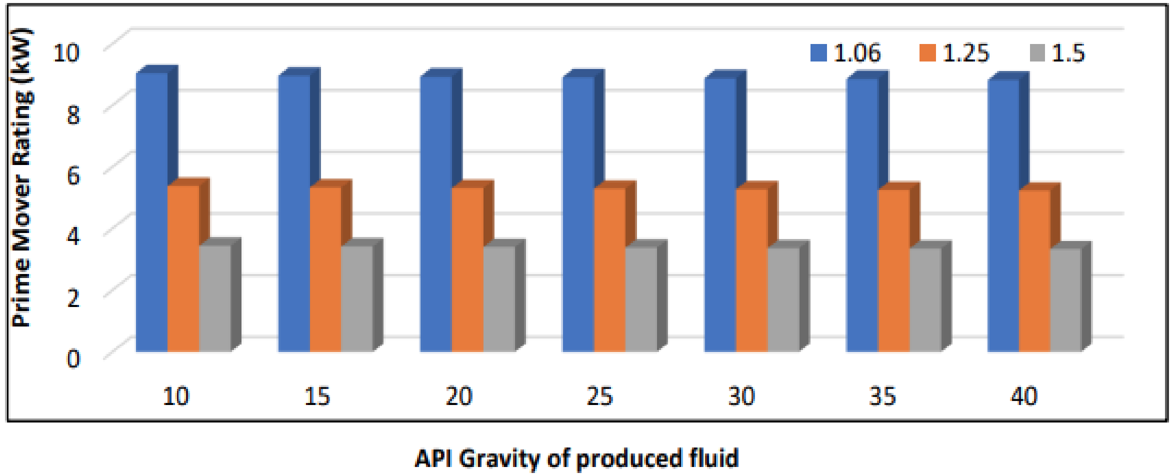

Fig 7 Effect of pump diameter on min. motor size

- The rating of the electric motor (prime mover) decreases with increases in the diameter of the pumps.
- hence a pump diameter of 1.5 inches is chosen.

- The energy requirement (minimum prime mover size in kW) generally decreases with an increase in the API gravity, from 10 to 40.
- API gravity of 25 is adopted in sizing the artificial lift system.

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Design and Analysis of Sucker Rod Pump

System Configuration

- The values derived from the parametric investigation are used in QRod to begin the iterative sizing.
- Steel Rod is chosen, and
- Target production rate of 100 barrels per day is set.

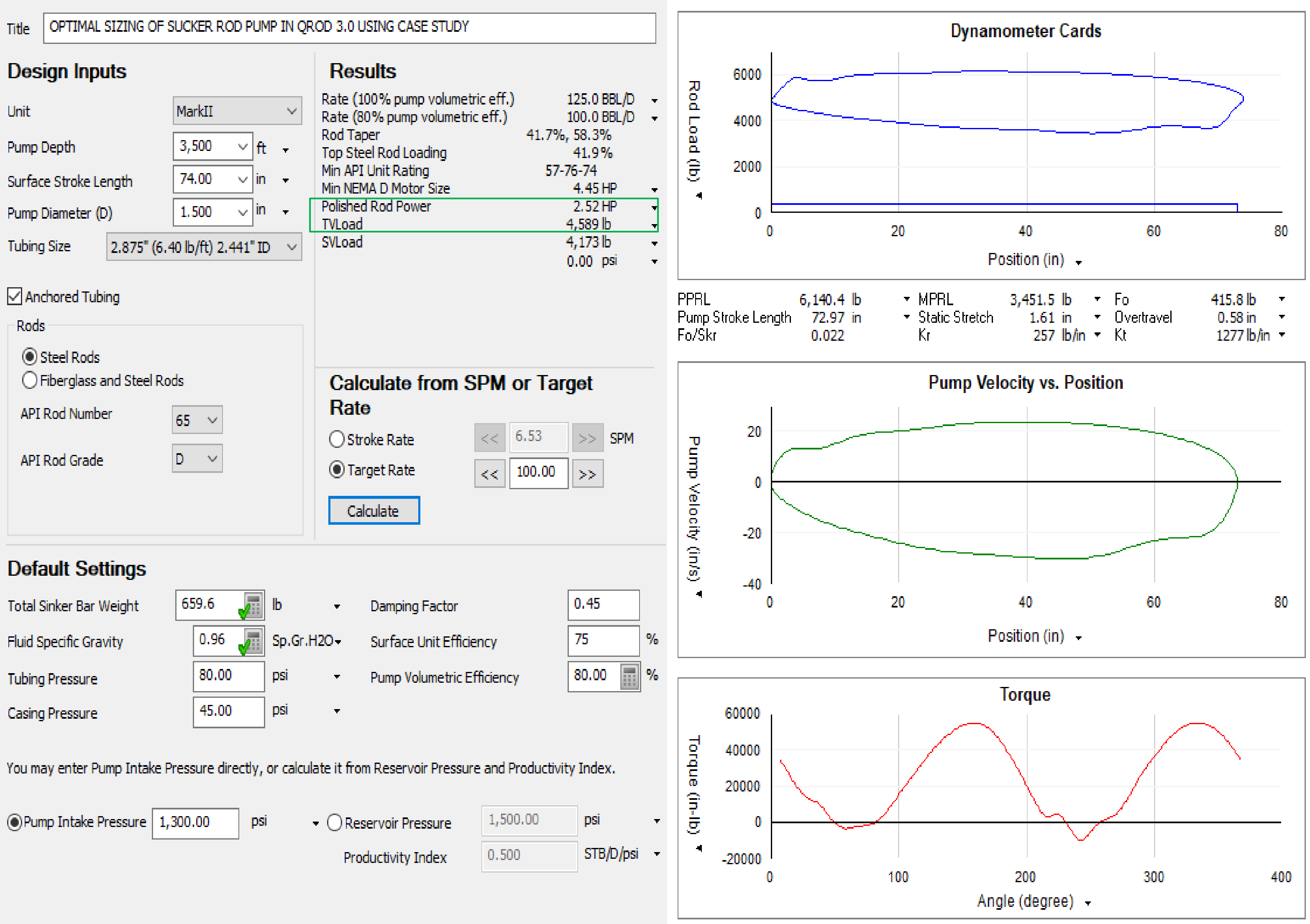

Fig 8 Design inputs and results after the parametric investigation in QuickRod

Design and Analysis of Sucker Rod Pump

System Configuration

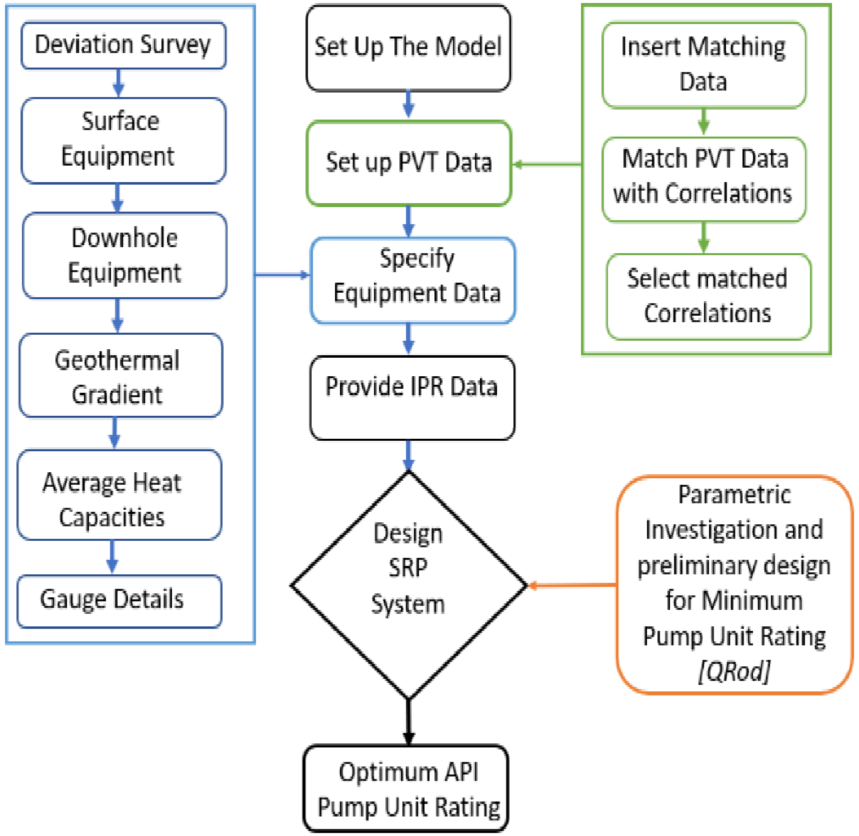

Fig 9 Integrated PROSPER™ + QRod™ Workflow

The artificial lift system sizing is independently implemented in both petroleum production system simulators after which the workflows are integrated to optimize the system sizing.

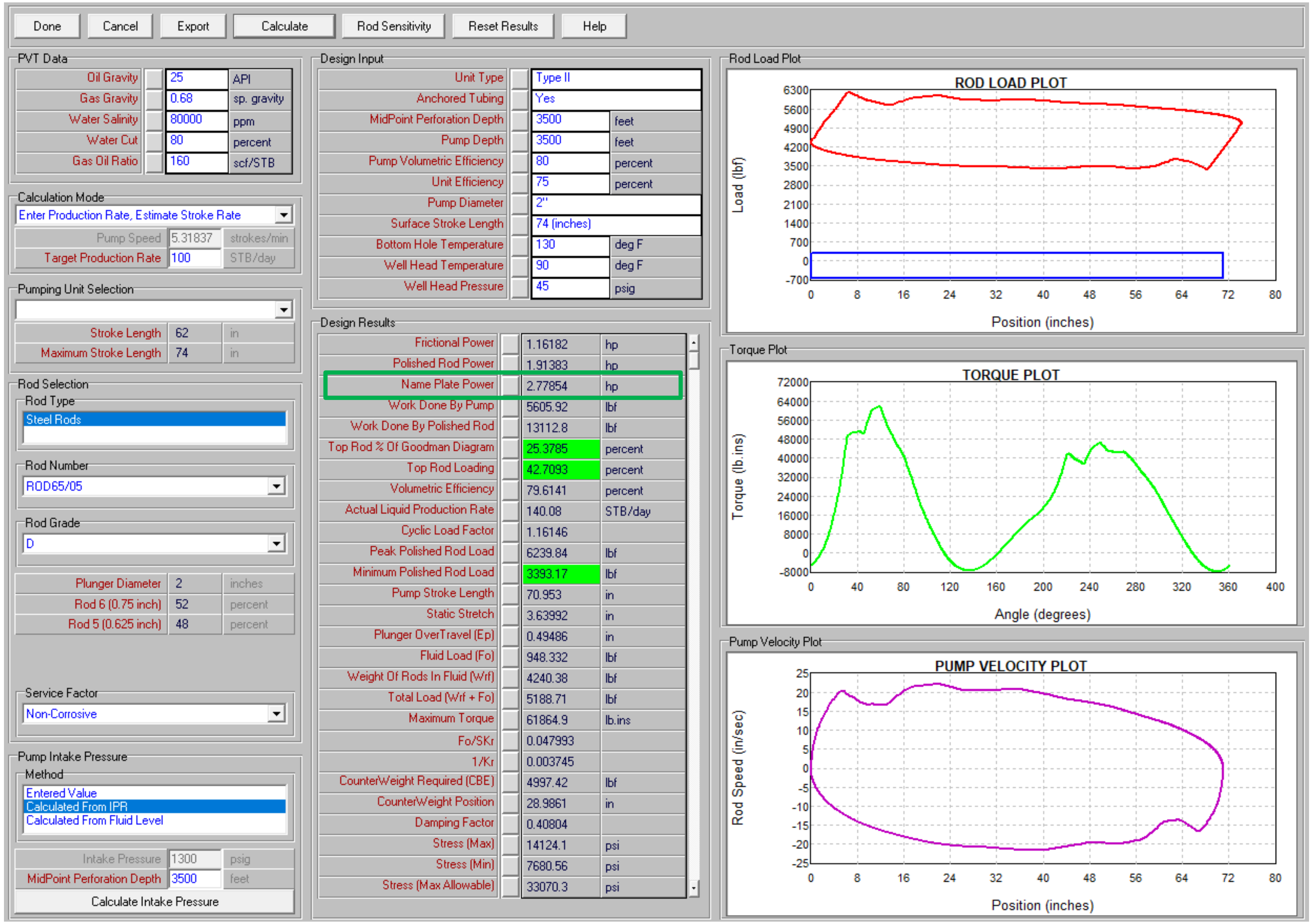

Fig 10 Sucker-rod pump artificial lift design in PROSPER™

Design and Analysis of Sucker Rod Pump

Results

Three sets of plots are typically obtained from artificial lift simulators, namely:

- rod displacement versus load/tension (pump dynamometer card)
- angular displacement versus mechanical torque (torque plot), and
- pump position versus pump velocity (velocity plot).

By identifying the *indices without integration* and comparing it *with the integrated performance* obtained with simulators, conclusions can be drawn.

The comprehensive design from the integrated workflow is given showing the design results. Three indices will be used in comparing the performance of the pump size obtained from the two design stages.

- Damped horsepower
- Cyclic load factor
- Prime mover rating

Table 1 key indices, comparing a single simulator with an integrated approach

Simulator	Min. NEMA D Motor Size (hp)	Polished Rod Power (hp)	Damped hp	CLF	Theoretical efficiency (%)
QRod	4.53	2.60	1.93	1.31	57.40
QRod + PROSPER	2.78	1.91	0.87	1.09	68.71

$$Theoretical\ efficiency\ (\%) = \frac{Polished\ Rod\ Power}{Minimum\ NEMA\ D\ Motor\ Size} \times 100\%$$

Table 2 Derating of High slip electric motor

HP	1 kW = 0.746HP	CLF	SF	Motor = (kW x CLF x SF)
2.78	2.07	1.09	1.15	2.59

Feasibility Study of Renewable Energy for Remote Oil Well

Site Description and Renewable energy potential of the selected location

- Medicine Hat is a city in southeast Alberta, latitude 50°2’32"N and longitude 110°48’49“W.
- It is one of the sunniest parts of Canada with an average of 2,544 sunshine hours and 330 days of sunshine per year. [12]
- Medicine Hat has the highest values for solar radiation and peak clearness index in the summer months, with a scaled annual average solar radiation of 3.61 kWh/m2/day.[13]
- The scaled annual average wind speed at 50 m above the earth’s surface for flat terrain in Medicine Hat is given as 5.70 m/s.[13]

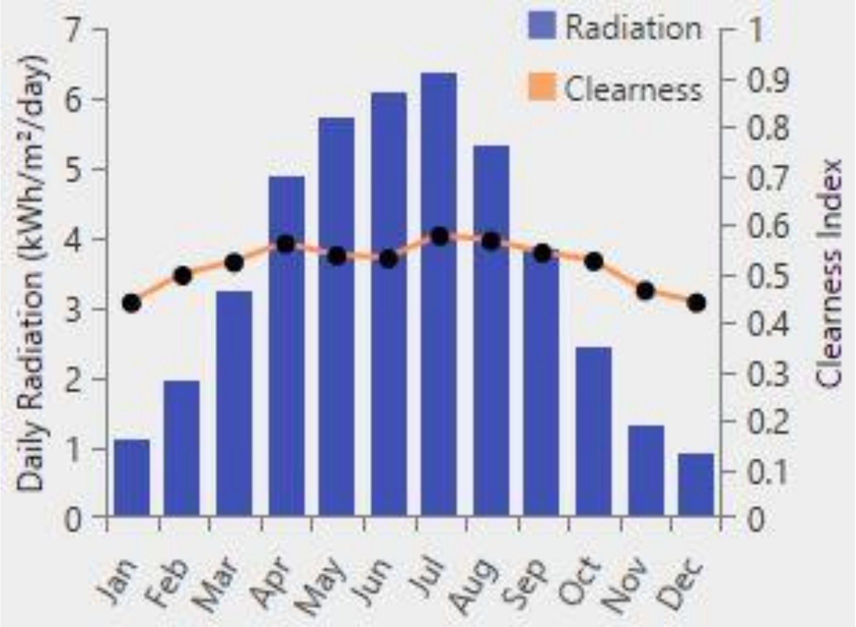

Fig 11 Monthly average solar radiation data (global horizontal Irradiance GHI) data in HOMER.

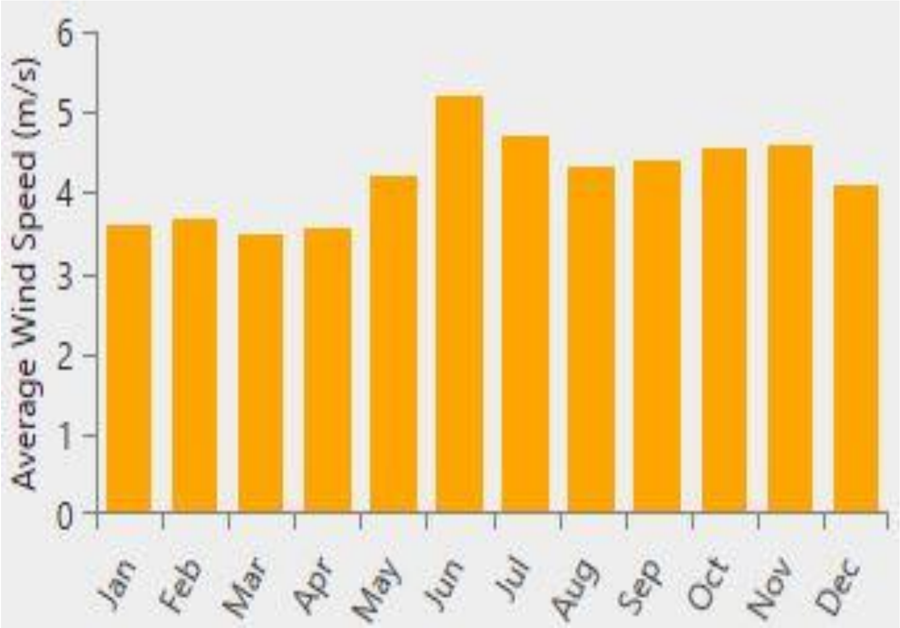

Fig 12 Monthly average wind speed plot for Medicine Hat.

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Feasibility Study of Renewable Energy for Remote Oil Well

Site Description and Renewable energy potential of the selected location

- The renewable microgrid evaluated for simulation entails hybrid generation and redundancy.
- It consists of two (2) primary power sources: solar PV and wind, one (1) backup source (battery storage) and the prime mover or high slip AC electric motor (NEMA D).
- The electrical energy from renewable energy generators will be used to power a high slip AC electric motor, which serves as the prime mover for the sucker-rod-pumped artificial lift system.
- The proposed system is matched with the requirement of the producing well and is to be 100% renewable to ensure minimal interruption of hydrocarbon production, reduce noise and eliminate exhaust gas pollution.

Feasibility Study of Renewable Energy for Remote Oil Well

Site Description and Renewable energy potential of the selected location

The case study is a remote oil well that cannot be connected to the grid for technical and/or economic reasons, hence is proposed to be powered by a small stand-alone hybrid renewable power system.

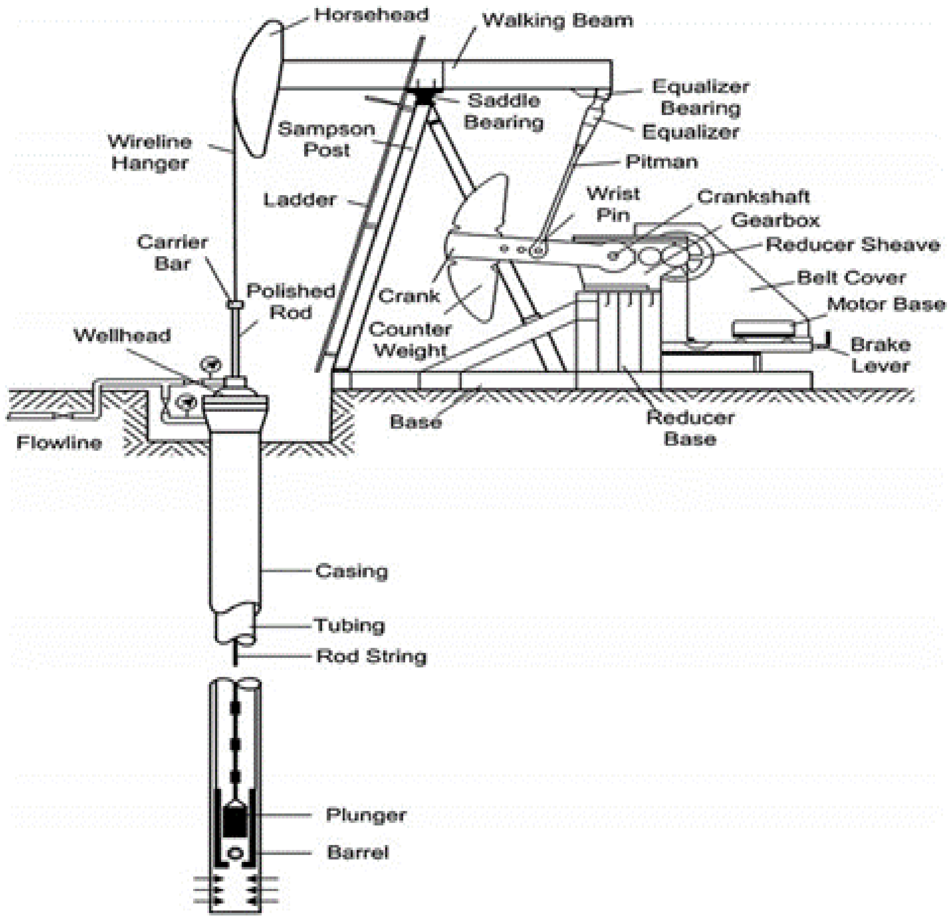

Fig 13 Sucker-rod pumping unit.[14]

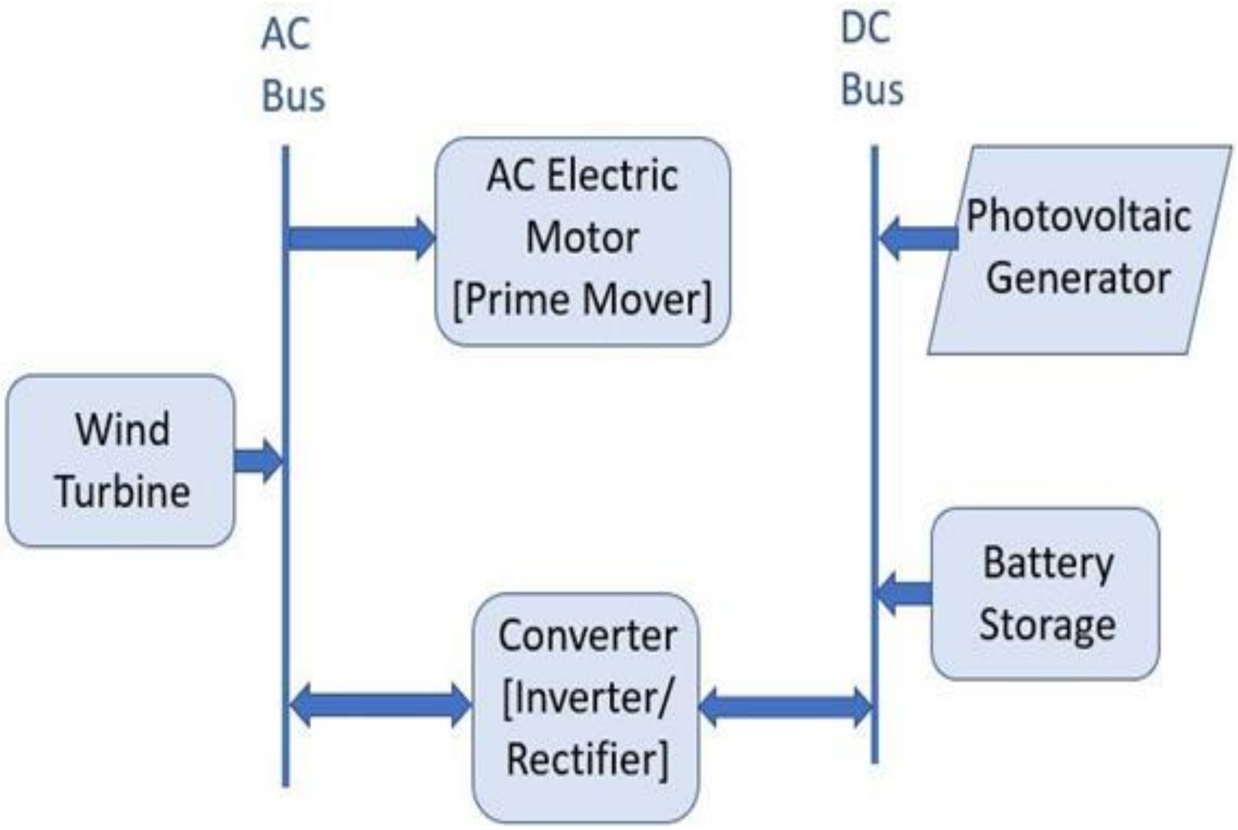

Fig 14 Sucker-rod pumping unit

Feasibility Study of Renewable Energy for Remote Oil Well

System Design and Description of Load Profile for the case study well

- **Scenario A**: Intermittent production (diurnal, during the day, 12 hours on, 12 hours off).

For intermittent production, the daily and monthly load profile, the pump is turned on for 12 hours of daylight from 7 am to 7 pm and off otherwise.

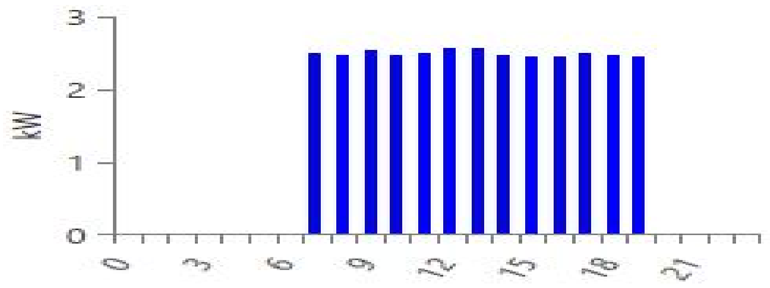

Fig 15 Daily load profile for scenario A: Intermittent production (diurnal, during the day).

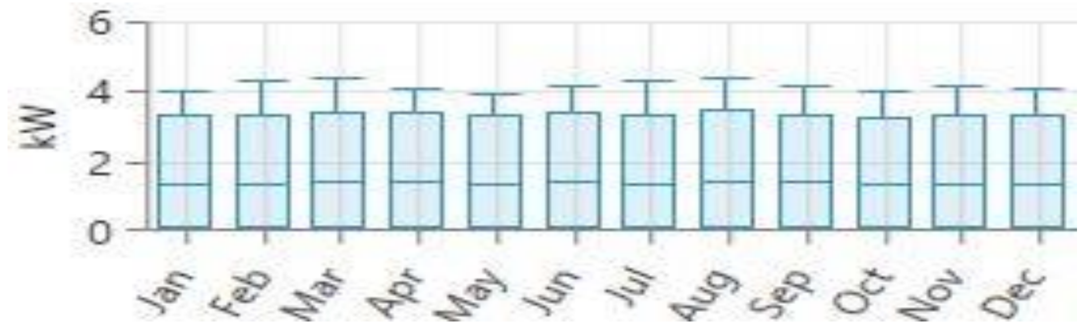

Fig 16 Monthly load profile for scenario A

- **Scenario B**: continuous pumping

For continuous production, the load is run continuously. It is expected that the cost contribution of the required storage system will be justified by the extra production made possible by continuous operation.

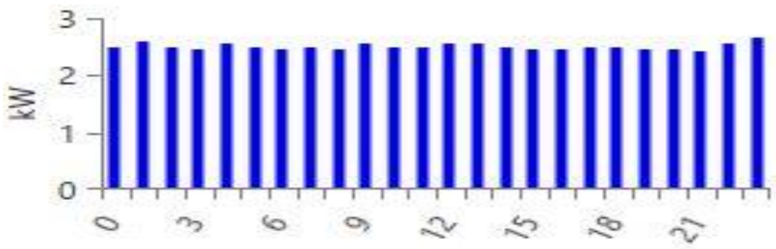

Fig 17 Daily load profile for scenario B: continuous pumping.

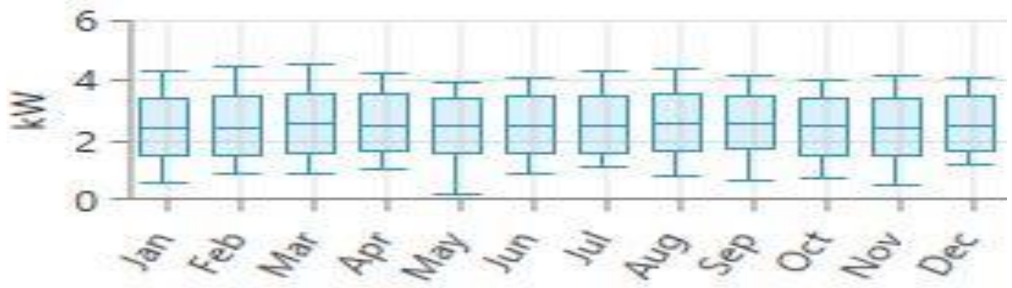

Fig 18 Monthly load profile for scenario B

Feasibility Study of Renewable Energy for Remote Oil Well

System Design and Description of Load Profile for the case study well

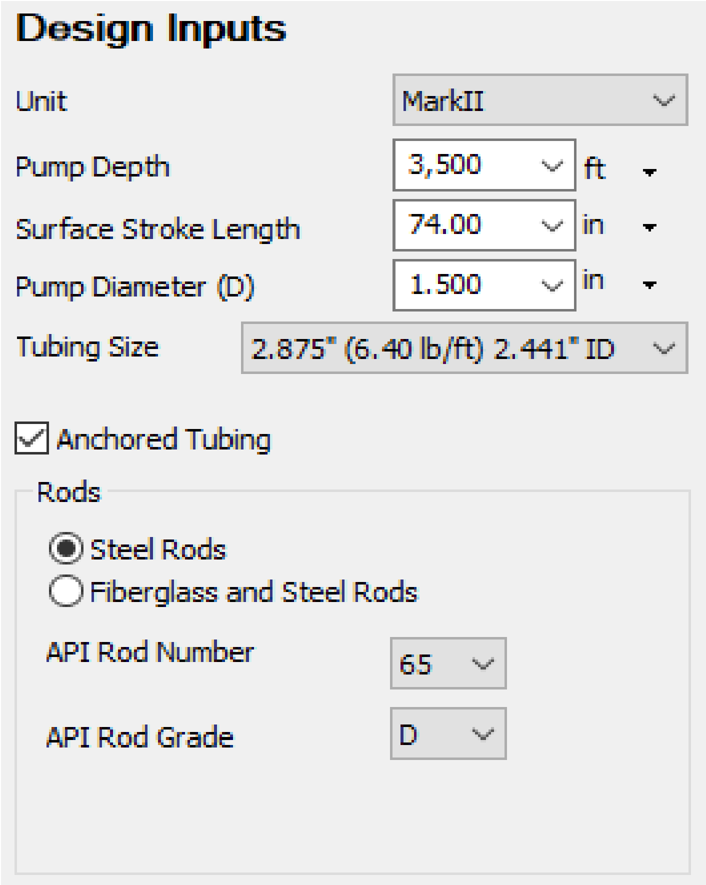

Fig 19 QuickRod Design Input

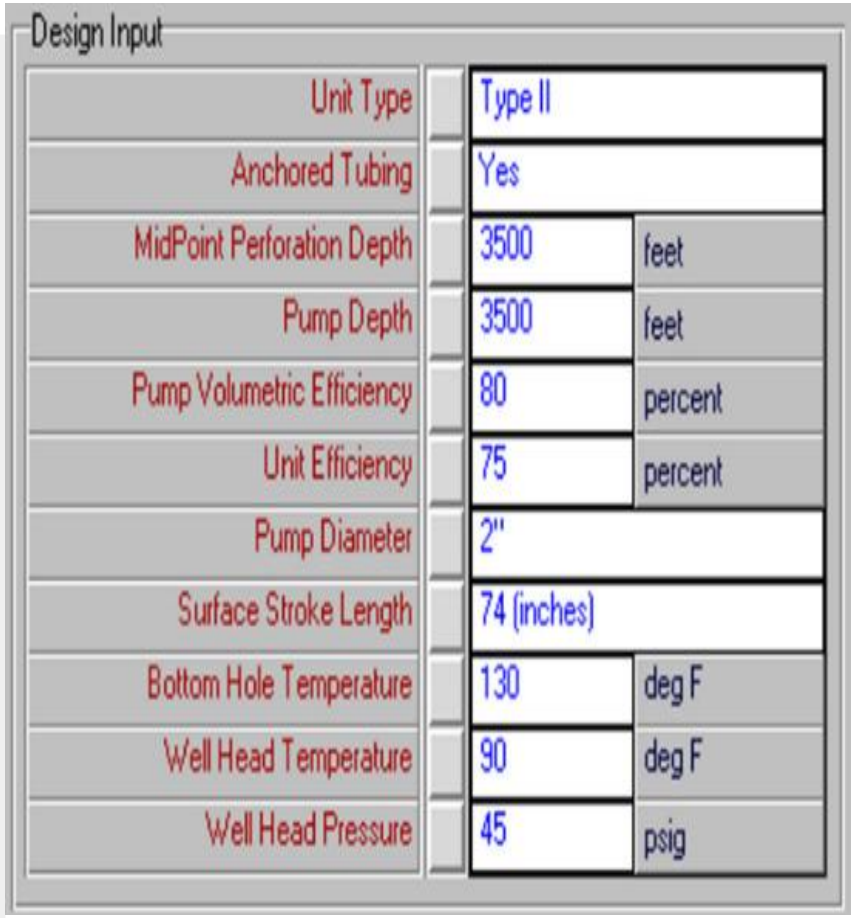

Fig 20 Prosper Design Input

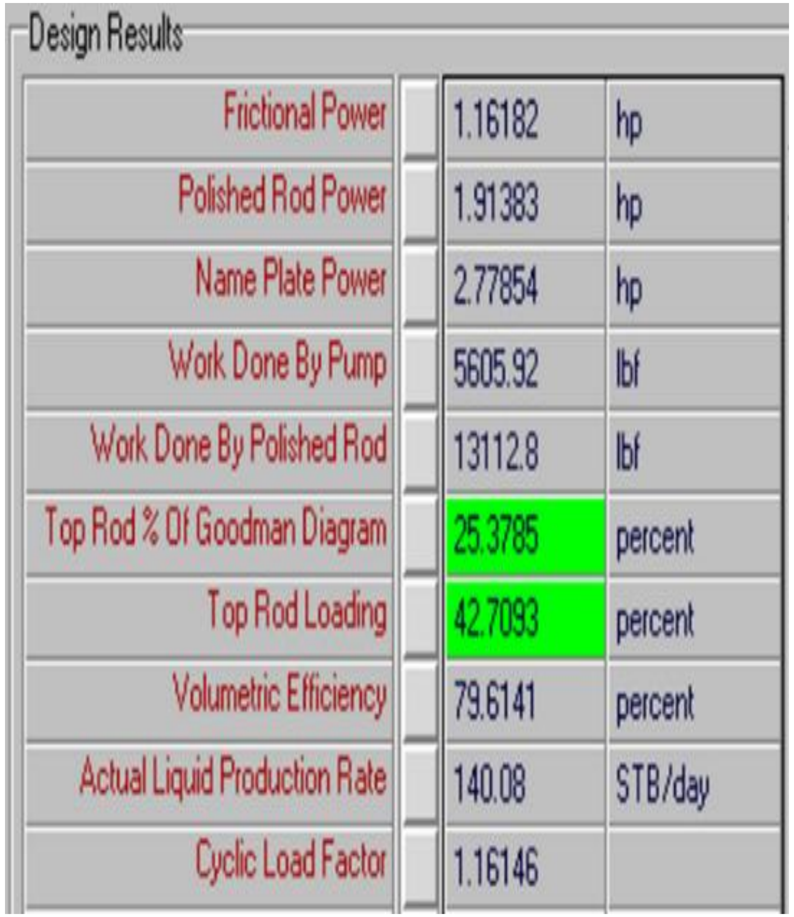

Fig 21 Size and power rating of pump required

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Feasibility Study of Renewable Energy for Remote Oil Well

System Configuration and Components of Renewable Power System

- From a continuous pumping load perspective, a continuous pumping load perspective, the energy consumption of the AC electric motor is 60.11 kWh/d, with a peak load of 4.55 kW.

- The system is designed with a discount rate of 8%, for 25 years and

- consists of **solar panels** (**Jinko Eagle PERC60, 300W**) with an efficiency of 18.33%, **deep cycle batteries** [**SAGM 12 205 (12V, 219Ah**)] with four (4) units per string to obtain a string voltage of 48 V.

- A 5.5 kW system converter (battery dedicated **inverter**: **Schneider Conext XW + 548**) was deployed with 93% efficiency.

- A **wind turbine** with a 4.5 m rotor and a hub height of 12 m (**AWS HC, 3.3 kW**) was also selected as a secondary energy source, as shown in the schematic of the system.

- The system structure for diurnal pumping is shown in Fig. 10, with a daily energy consumption of 32.43 kWh/d and a peak load of 4.44 kW

- The proposed design should economically exploit solar energy, wind energy, or both, with battery storage to sustain hydrocarbon production.

Feasibility Study of Renewable Energy for Remote Oil Well

System Configuration and Components of Renewable Power System

System structure optimized in HOMER with components integrated

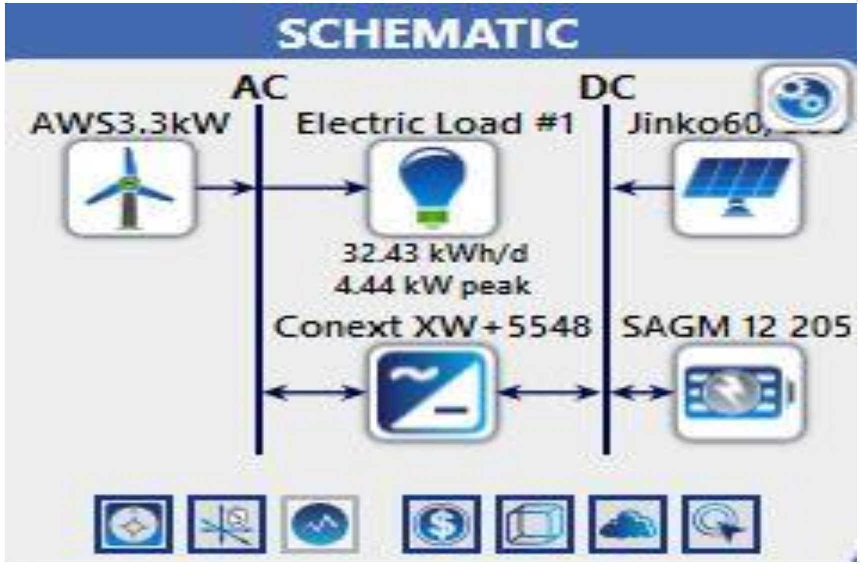

Fig 22 intermittent pumping

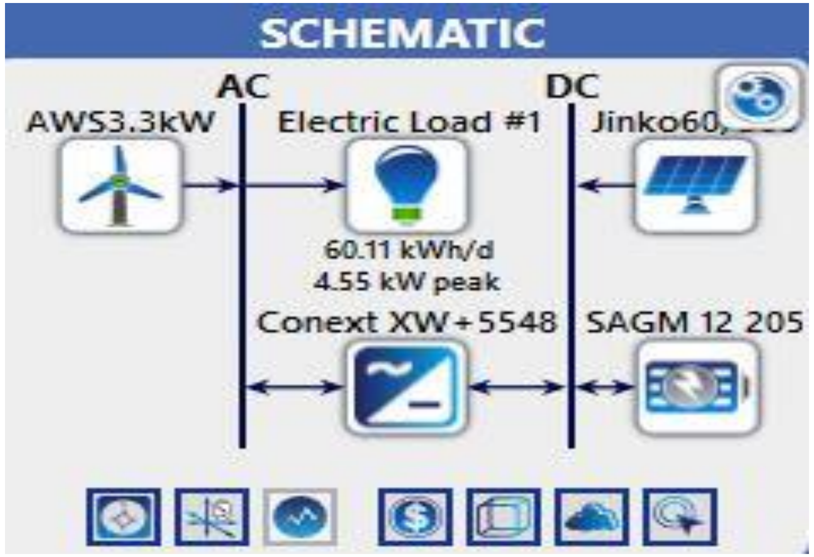

Fig 23 Continuous pumping

- A total of 1,204 solutions were simulated, 578 were feasible
- For intermittent pumping pumping, the daily energy consumption of the AC electric motor is 32.43 kWh/d with a peak load power demand of 4.44 kW.

- A total of 1,538 solutions were simulated
- For continuous pumping, the daily energy consumption of the AC electric motor is 60.11 kWh/d, with a peak load power demand of 4.55 kW

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Feasibility Study of Renewable Energy for Remote Oil Well

System Configuration and Components of Renewable Power System

Scenario A: **Intermittent production** (diurnal, during the day)

Fig 24 Monthly electricity (1A) (PV + Battery).

Fig 25 Monthly electricity (2A) (PV + Battery + Wind).

Fig 26 Monthly electricity (3A) (PV + Battery + Wind).

Table 3. (a) Simulation results by system types or categories for intermittent production **(b) Cost of system types for intermittent production.**

Architecture					Cost				System	
Jinko60/300 (kW)	AWS3.3kW	SAGM 12 205	Conext XW+5548 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
27.3		64	4.49	CC	$64,969	$0.425	$1,318	$47,932	100	0
26.4	1	60	4.12	CC	$89,512	$0.585	$1,466	$70,563	100	0
	4	80	3.80	CC	$157,555	$1.03	$1,863	$133,474	100	0

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Scenario B: Continuous production

Fig 27 Monthly electricity (1B) (PV + Battery).

Fig 28 Monthly electricity (2B) (PV + Battery + Wind).

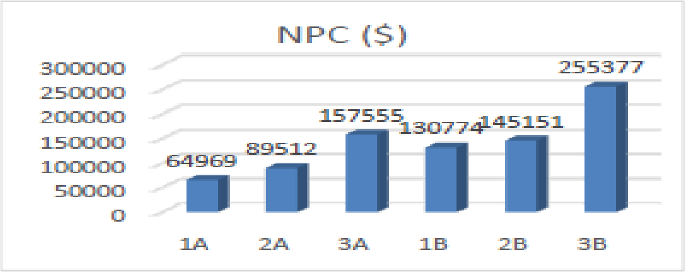
Fig 29 Monthly electricity (3B) (PV + Battery + Wind).

Table 4. (a) Simulation results by system types or categories for continuous production **(b) Cost of system types for continuous production.**

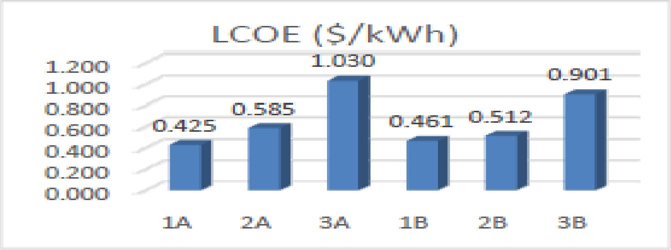
Architecture					Cost				System	
Jinko60/300 (kW)	AWS3.3kW	SAGM 12 205	Conext XW+5548 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
50.8		128	4.89	CC	$130,774	$0.461	$3,163	$89,883	100	0
50.8	1	104	4.67	CC	$145,151	$0.512	$3,056	$105,644	100	0
	6	160	6.54	CC	$255,377	$0.901	$3,095	$215,369	100	0

Feasibility Study of Renewable Energy for Remote Oil Well

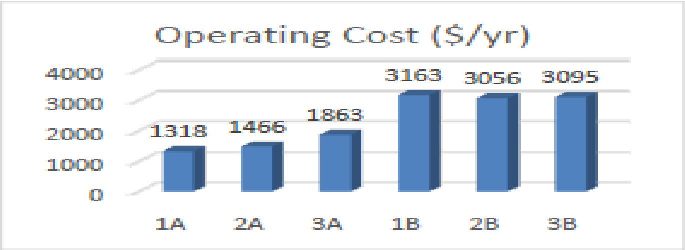
Discussion of Results



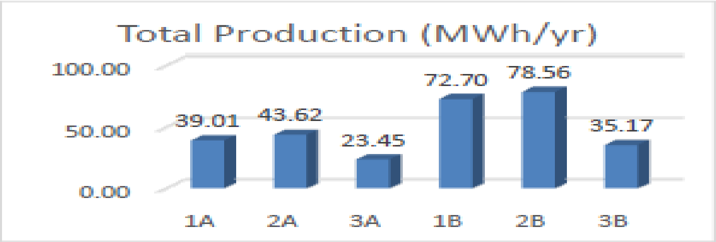
(a) Net present Cost for each architecture



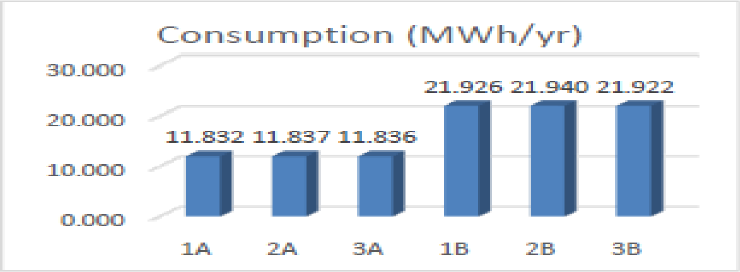
(b) LCOE for each architecture



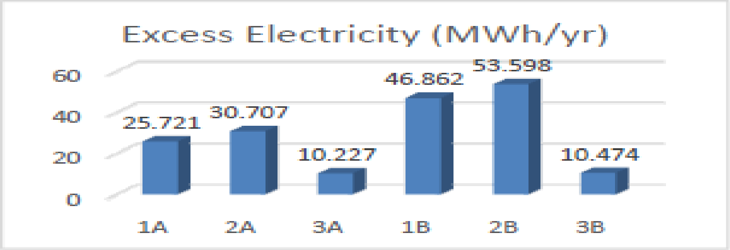
(c) Operating cost for each architecture



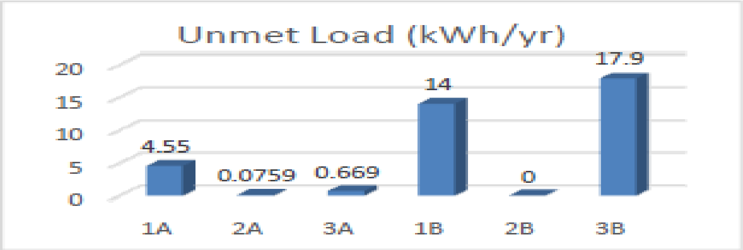
(d) Total production for each architecture



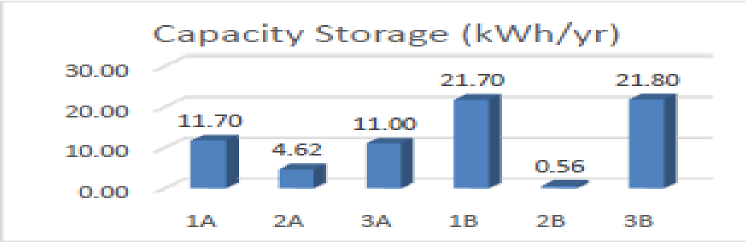
(e) Power Consumption for each architecture



(f) Excess generated electricity for each architecture



(g) Unmet load for each architecture



(h) Capacity storage for each architecture

- Type 3 (wind turbine + battery storage) will be ignored in the analysis as it has the highest overall cost of the feasible system configurations.
- System type 1 (**solar photovoltaic + battery storage**) is **least cost** consideration, irrespective of load scheduling
- System type 2 (**solar photovoltaic + wind+ battery storage**) results in a higher level of excess electricity, a lower amount of unmet load and lower capacity storage compared to system 1.
- Hence type 2 has higher net present cost and higher levelized cost of energy than type 1.
- Hybrid renewable power generation with continuous pumping (**2B**) is seen to have the least amount of unmet load (0 kWh/yr) for all the system types and pumping configurations.

Fig 30 (a) to (e) compares indices for continuous and intermittent pumping for the six renewable architectures.

Feasibility Study of Renewable Energy for Remote Oil Well

Discussion of Results

Table 5 Showing Variation in NPC, COE and Unmet load (%)

	SR ($kWh/m^2/day$)	WS (m/s)	PV (kW)	WT (kW)	BS (St)	NPC ($1,000)	COE ($)	Unmet (%)
2B	*0.93*	*5.1*	*8.09*	*8*	*30*	*304*	*1.07*	*0.0494*
	0.93	*5.7*	*20.5*	*5*	*29*	*229*	*0.81*	*0.0546*
	0.93	*6.32*	*4.87*	*5*	*30*	*213*	*0.75*	*0.0583*
	3.61	5.1	50.8	-	32	131	0.46	0.0636
	3.61	5.7	50.8	-	32	131	0.46	0.0636
	3.61	6.32	50.8	-	32	131	0.46	0.0636
1A	6.38	5.1	25.2	-	27	98	0.35	0.0797
	6.38	5.7	25.2	-	27	98	0.35	0.0797
	6.38	6.32	25.2	-	27	98	0.35	0.0797

- The variation in NPC, COE, and unmet load (%) due to variation in daily solar radiation and average wind speed

- Below the average daily solar radiation (3.61 kWh/m2/day), the hybrid renewable energy system **(solar photovoltaic, wind turbine and battery storage: type 2)** is the most preferred architecture with the least unmet load percentage and highest system NPC and LCOE.

- Above the mean daily solar radiation (3.61 kWh/m2/day), **type 1 (solar photovoltaic and battery storage)** is the preferred architecture with the least system cost and slightly higher unmet load than type 2.

Comparing systems 1 and 2:

- System type 1, **minimizes** [net present cost, levelized cost of energy, total production, consumption, and excess electricity], while

- System type 2, **minimizes** [unmet load, capacity storage].

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Feasibility Study of Renewable Energy for Remote Oil Well

Results

Table 6 Proposed feasible solutions.

Solar PV	Type 1A	Type 2B	Unit
Rated capacity	27.3	50.8	kW
Mean output	4.45	8.30	kW
Mean daily output	107	199	kWh/d
Capacity factor	16.3	16.3	%
Hours of operation	4,377	4,377	hrs/yr
PV penetration	330	331	%
Wind			
Total rated capacity		3.30	kW
Mean output		0.669	kW
Total production		5,862	kWh/yr
Capacity factor		20.3	%
Hours of operation		7,329	hrs/yr
Wind penetration		26.7	%
Battery			
Number	64	128	(4bt/string)
String in parallel	16	32	Strings
Bus voltage	48	48	V
Nominal capacity	168	336	kWh
Usable nominal capacity	118	235	kWh
Energy in	3,860	15,244	kWh/yr
Energy out	3,294	12,982	kWh/yr

- The major criteria of which configuration to choose depends on :
  system cost, **total unmet load** and **unmet load fraction**
- The hybrid generator option: **type 2B** for continuous pumping, is preferred in wells where the production due to the extra pumping hours can justify the higher system cost incurred over the life of the well.
- The lowest system costs are incurred at the highest mean daily solar radiation and average wind speeds
- Solar photovoltaic and battery storage type 1A for intermittent pumping is the least cost alternative
- Using the least unmet load criteria, hybrid generation: solar PV, wind and battery storage in continuous pumping has been demonstrated to have the least unmet load and capacity storage with 0 kWh/yr of unmet load, capacity storage of 0.56 kWh/yr, a net present cost of $145,150.50, a levelized cost of energy of $0.51/kWh and an operating cost of $3,056.04/yr.
- Using the least cost criteria, solar PV and battery system in intermittent pumping has been demonstrated to be the most preferred with 4.55 kWh/yr of unmet load, capacity storage of 11.70 kWh/yr, a net present cost of $64,969, a levelized cost of energy of $0.425/kWh and an operating cost of $1,318/yr.

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Open-Source, IoT Based SCADA System for Remote Oil Well

System Description

- The essential nature of oil production requires continuous site monitoring to acquire, log, and process the data so that timely intervention can ensure continuous and optimal operation.

- The case study is a low-flowrate oil well artificially lifted with a pump jack, driven by an electric motor and powered by solar energy.

- The system implements a low-cost, open-source IoT-based SCADA system for remote monitoring and control of oil and gas facilities using Node-RED and Arduino microcontrollers.

- The system integrates multiple sensors (temperature, flow rate, water level, voltage, current, position, accelerometer, distance) and actuators (motors) into the SCADA system.

- A web-based graphical user interface (GUI) is developed using Node-RED for real-time visualization, data logging, and remote access to sensor data and control functions.

- The system uses a secure remote access solution for the SCADA system using port forwarding, network address translation (NAT), and HTTP basic access authentication with Nginx.

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Open-Source, IoT Based SCADA System for Remote Oil Well

System Description

- The IoT-based open-source SCADA system consists of three subsystems, a master terminal unit, and two terminal units.

- The design and implementation of the SCADA system involves hardware and software selection .

- Each sensor directly collects onsite data for key parameters which are analysed in the Arduino integrated development environment (IDE) and then logged and processed for monitoring and visualization.

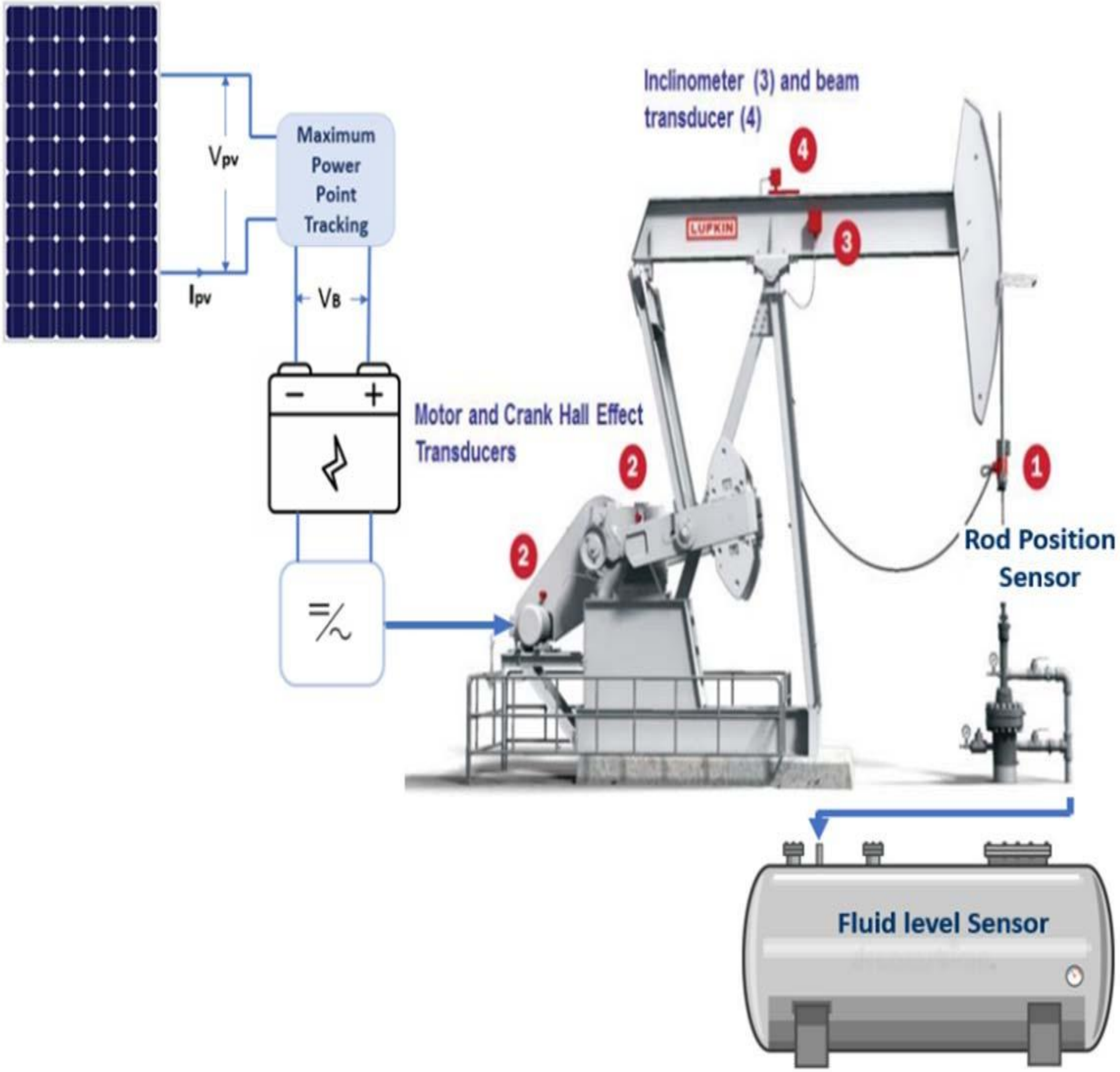

Fig 31 Schematic diagram of the production system.

Open-Source, IoT Based SCADA System for Remote Oil Well

Implementation Methodology

- The system is designed for monitoring, supervision, and remotely controlling motors and sensors deployed for oil and gas facilities.

- The IoT-based open-source SCADA system consists of three subsystems, a master terminal unit, and two terminal units.

- The design and implementation of the SCADA system entail hardware and software selection

- each sensor is then programmed in the Arduino integrated development environment (IDE).

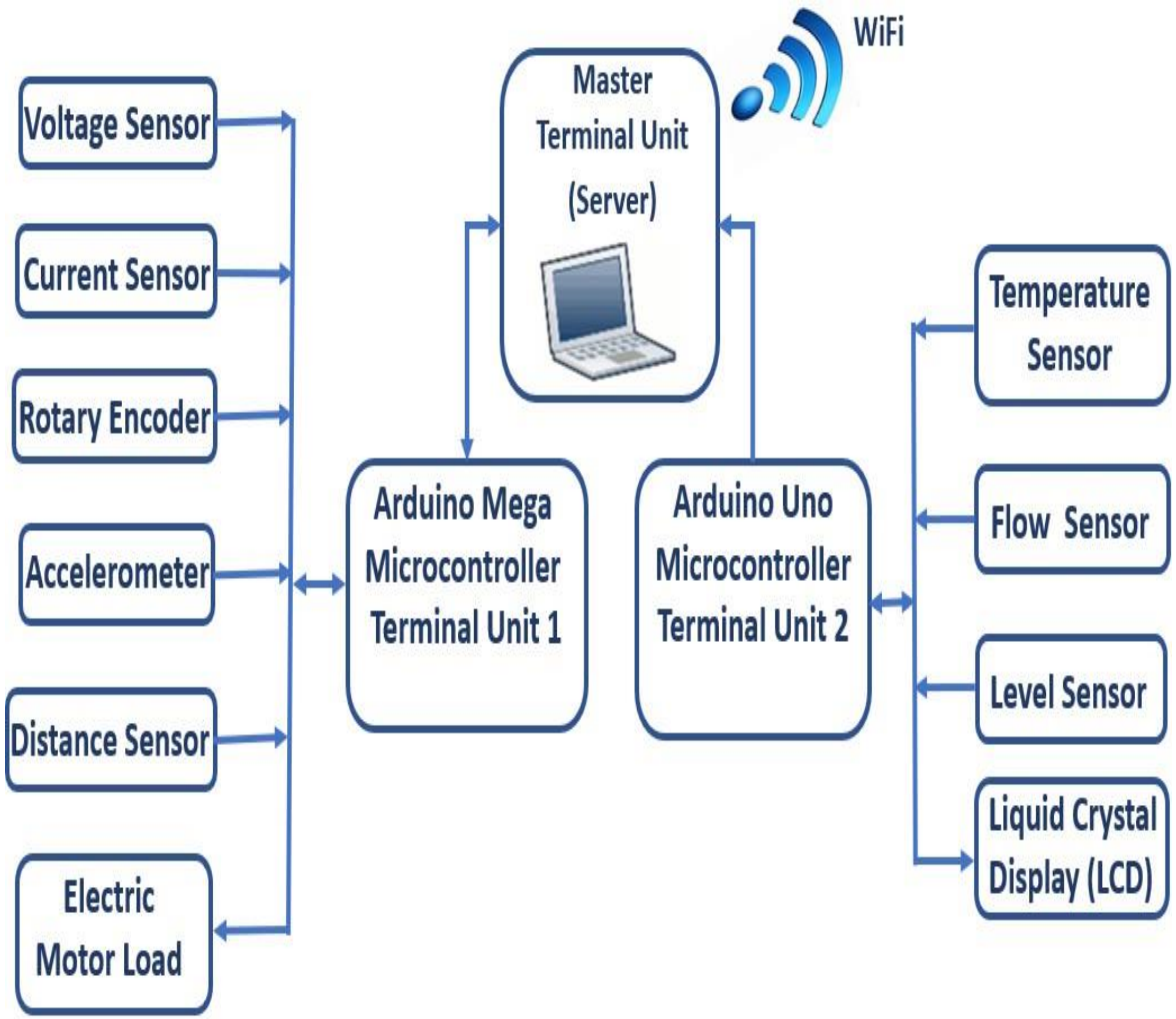

Fig 32 Schematic of IoT-based SCADA System

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Open-Source, IoT Based SCADA System for Remote Oil Well

Web Interface

- The design methodology is to provision the web server on the local computer and make it accessible from the Internet,

- Client requests to the Node-RED application running on the webserver are transferred from the external IP address, and port of the router to the internal IP address and port of the local server (port forwarding) and

- Server responses are in turn transferred from the webserver to the router (network address translation, NAT) and on to the respective client.

- Port forwarding is implemented by mapping the internal IP address/port of the server to that of the router.

- This option exposes the Node-RED server on the Internet for remote access.

- Hence, a basic access authentication is implemented using Nginx. Nginx requires the internet client to provide a username and password before access to the Node-RED on the server is granted, hence improving the security, are shown.

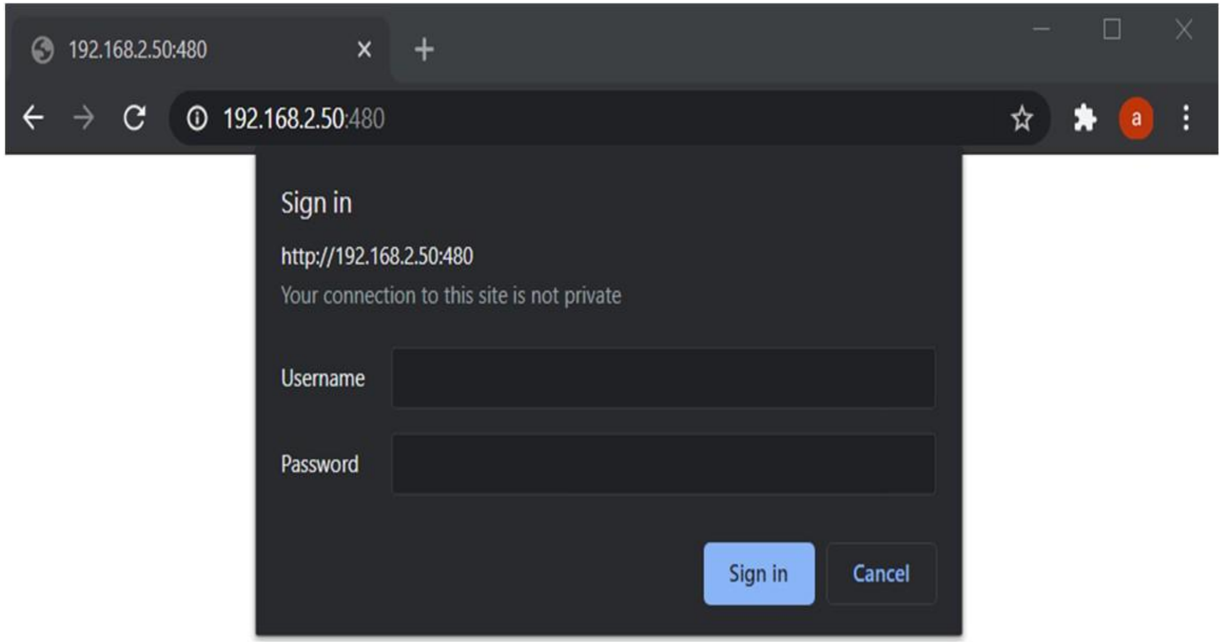


Fig 33 Access Authentication for Web Interface:
NGINX client access authentication page when logging in to the server.

Open-Source, IoT Based SCADA System for Remote Oil Well

Node-RED IoT Platform on the Local Server : Node-RED process flows for all Sensors required

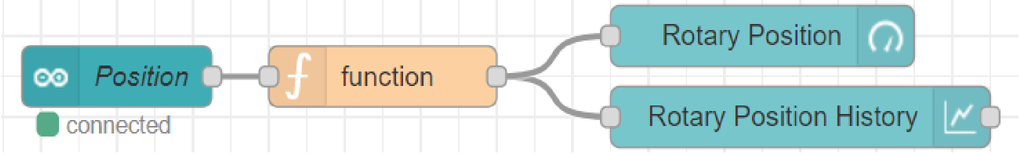


Fig 34 Process flow for Position sensor

Senses and Displays the position of the sucker rod

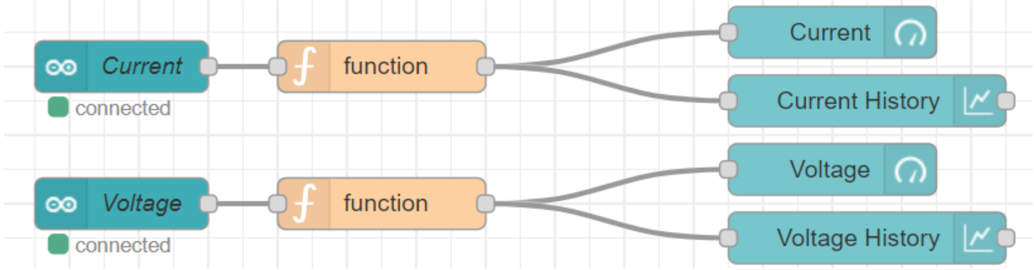


Fig 35 Process flow for the current and voltage sensor

Monitors the voltage and current for the prime movers driving the sucker rod pump

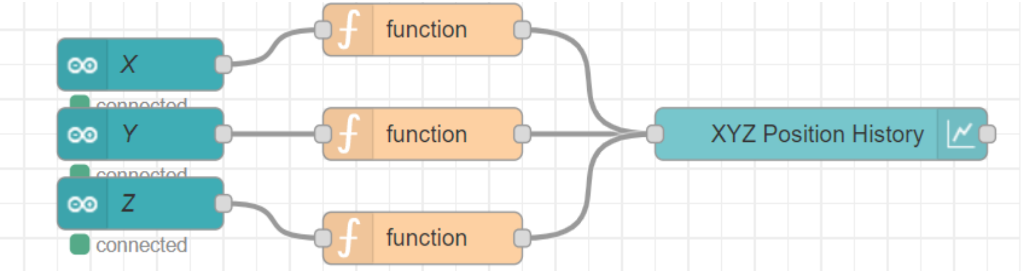


Fig 36 Process flow for the accelerometer

Measures the changes in the pumping speed to track pump behavior and detect pump inefficiencies

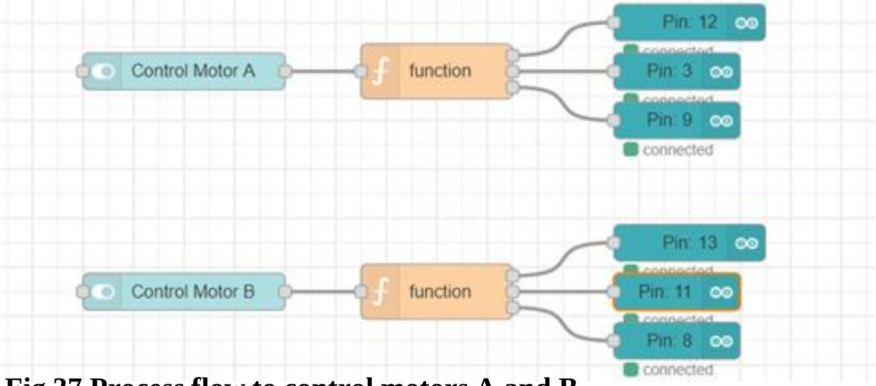


Fig 37 Process flow to control motors A and B

Two DC gear motors re used to model the rotational output from the electric motor prime mover which drives the sucker rod pump

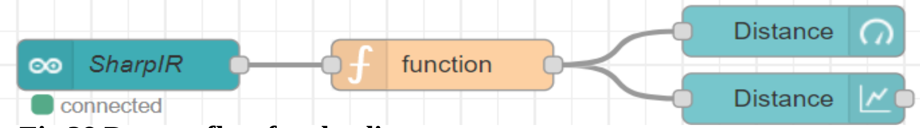


Fig 38 Process flow for the distance sensor

The flow sensor detects the distance travelled by the sucker rod string from a reference datum

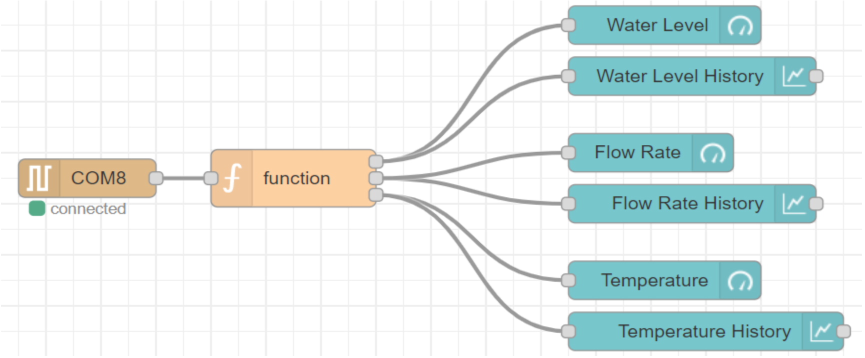


Fig 39 Process flow for the level, flowrate and temperature sensor

The fluid flow, level and temperature sensor track the flow rate, volume and temperature of the produced fluid from the subsurface, through pipelines to storage tanks

Open-Source, IoT Based SCADA System for Remote Oil Well

Hardware Design, Experimental Setup, and Implementation

- All the IoT sensors, motors, and display are laid out
- As shown in this figure, the Server is available on a local host computer and serves as the **master terminal Unit**
- The **remote terminal units** : **Arduino Mega** and **Uno** are connected to the local server via USB ports.
- The Arduino Mega and Uno are connected to the computer via USB ports.
- In this experimental setup, all the sensors, motors, and display are laid out
- The graphic user interface (GUI) is also available in Node-RED and contains a dashboard with logs and charts for the visualization of sensor data in real-time.

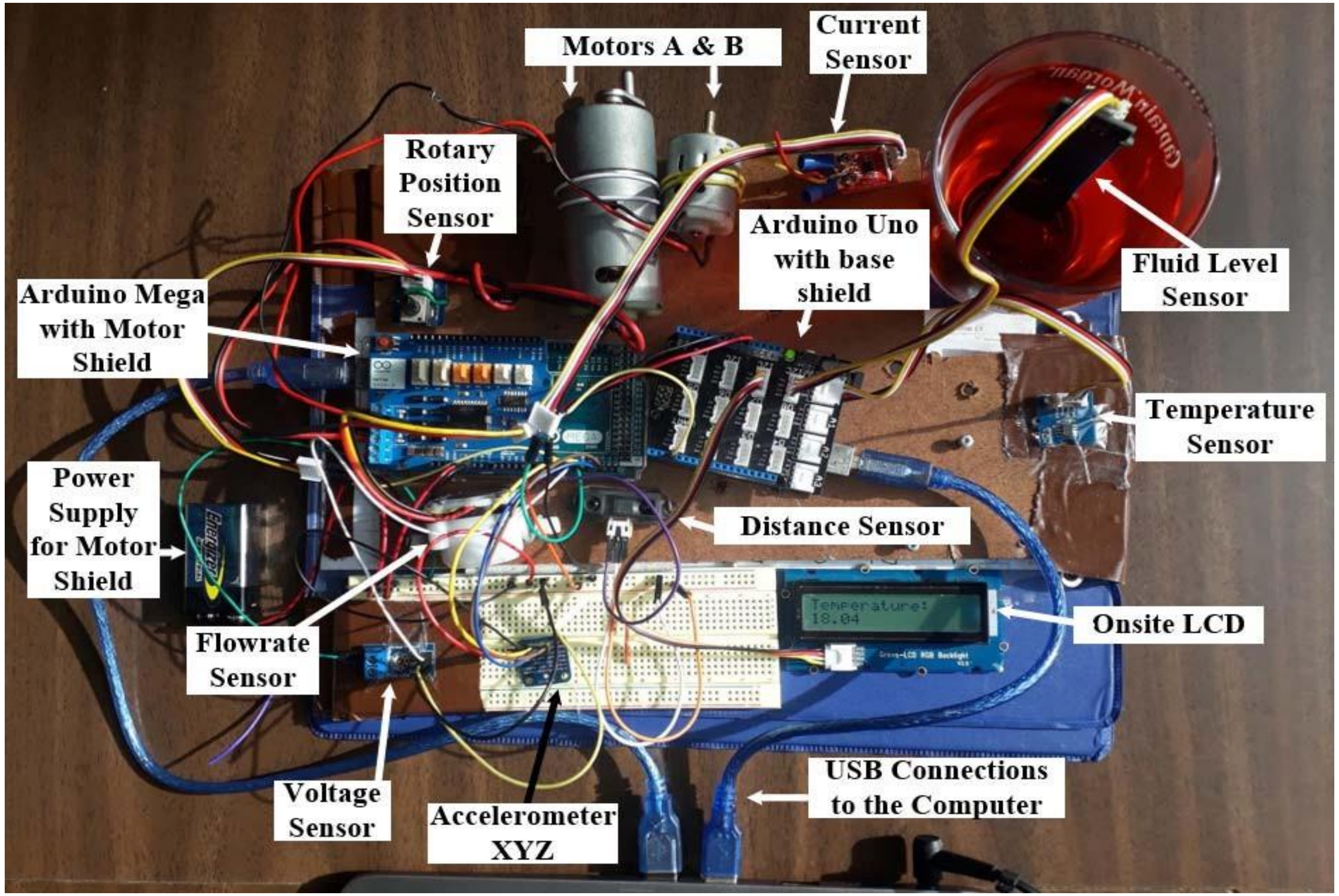


Fig 40 Experimental setup of the proposed IoT-based SCADA system

Open-Source, IoT Based SCADA System for Remote Oil Well

Results : Charts and gauges (System 1)

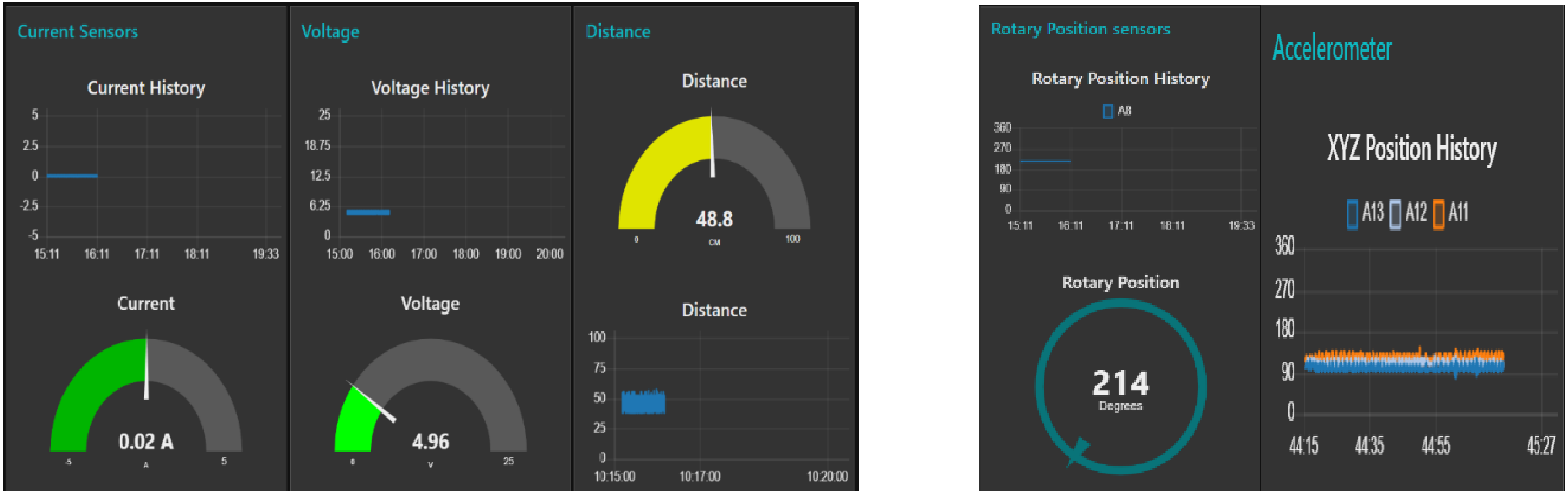


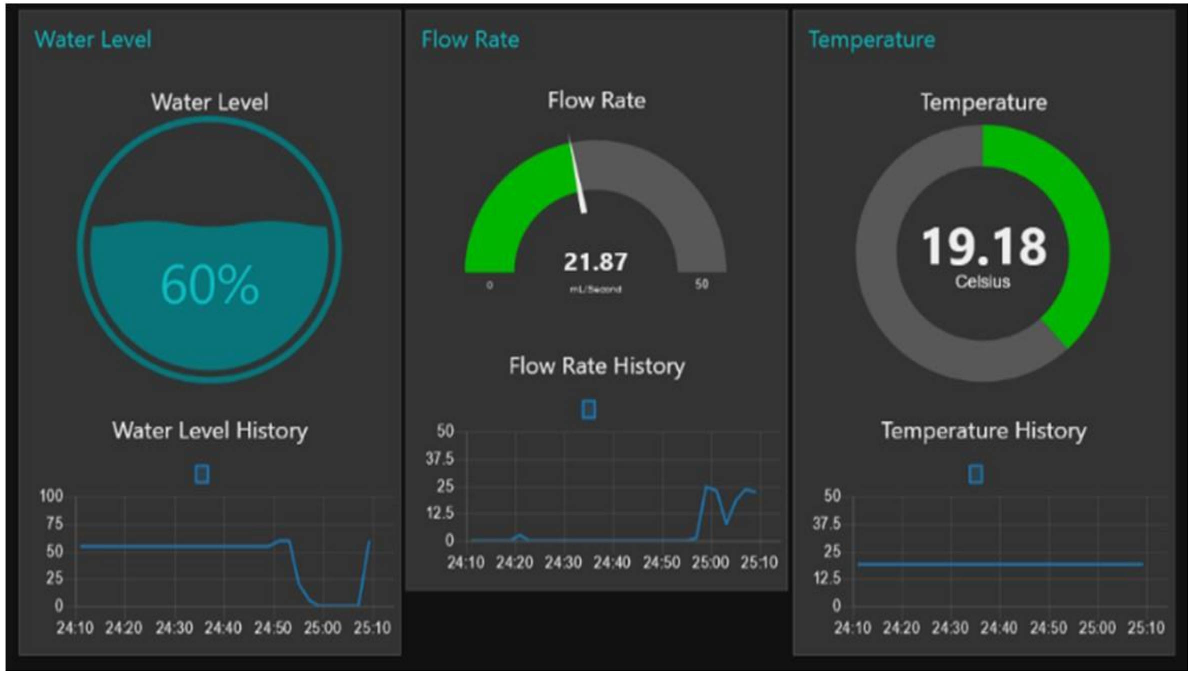
Fig 41 (a) Current (b) Voltage (c) Distance (d) Accelerometer (e)Position

Subsystem 1: **Arduino Mega**

- The dashboard for sensors connected to Arduino Mega
- The dashboard for this subsystem includes gauge and chart outputs for current, voltage, distance, rotary position, and accelerometer sensors.
- In this work, the user interface shows the received sensor data, both as a gauge and a chart.

Open-Source, IoT Based SCADA System for Remote Oil Well

Results : Charts and gauges (System 2 &3)



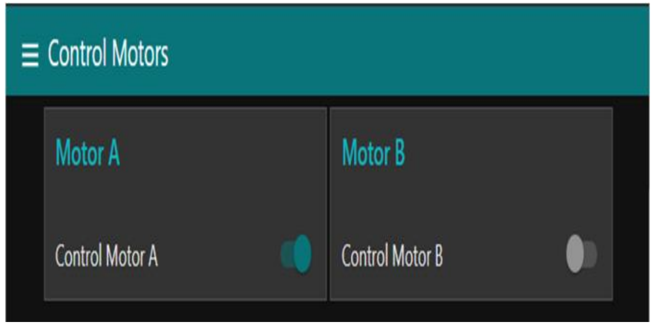


Fig 41 (f) Water Level (g) Flowrate (h) Temperature (i) Control of motors A and B

Subsystem 2

- The dashboard for the sensors on Arduino Uno is shown
- It is available in Node-RED as a web GUI that updates or responds in real-time.
- The user interface shows the sensor data both as a gauge and a chart.
- It shows the water level, flow rate, and temperature.

Subsystem 3

- shows the dashboard panel to control motors A and B connected to Arduino Mega's motor shield.
- This dashboard uses Arduino nodes in Node-RED and Firmata on the microcontroller to start and stop the motors.

- Monitoring of the oil well site parameters such as **flowrate from the producing well** and comparing it with the **speed of the electrical motor** is imperative to diagnose problems in an actual producing well.

- When the speed of the electric motor is high, and the flow rate of the produced fluid is declining, it could be an indicator of a fluid pound or gas lock in the rod pump downhole. It could also point to sand production at the producing interval or issues in reservoir production.

- **Early-onset of flow assurance problems** such as wax and paraffin formation could also be detected by **tracking** and **monitoring the behavior of the voltage and current** drawn by the electric motor and mapping trends, which could be further **corroborated with flow rate** and cross-referenced with **downhole temperature** and **pressure gauges**.

- When the **IoT devices are mounted on an actual 3D models** and data acquired logged appropriately, these sensor trends could be aggregated into historical data and analyzed for prediction of failure or monitoring production performance.

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

System Description : Choice of Renewable Energy System

- Electricity cost constitutes a significant part of the overheads incurred in producing wells and with these wells sufficiently remote from the electric grid, onsite generation of 100 % renewable energy presents a promising opportunity to invest in onsite renewable energy [15].

- This study presents a comprehensive methodology for the design, dynamic modelling, simulation, and control of a solar-powered sucker rod oil pump

- It combines load modelling of the sucker rod pump using SolidWorks with design, dynamic modelling, simulation, and control of the solar microgrid in Matlab's Simscape and Simulink.

- This approach combines the solar photovoltaic system, battery charge control system, battery energy storage system, step-up transformer, and the squirrel cage induction motor, which serves as the electric motor prime mover

- The surface pump model is first developed in SolidWorks and then converted to Simscape, the rating of the pump is then implemented as a load in the solar-powered electrical microgrid.

Table 7 Comparing 100% Solar with 100% (Solar + Wind)

Criteria	Continuous Pumping with Hybrid Generation (Solar PV, Wind, Battery Storage)	Intermittent Pumping with Solar PV and Battery System
Unmet Load	0 kWh/yr	4.55 kWh/yr
Capacity Storage	0.56 kWh/yr	11.70 kWh/yr
Net Present Cost (NPC)	$145,150.50	$64,969
Levelized Cost of Energy	$0.51/kWh	$0.425/kWh
Operating Cost	$3056.04/yr	$1318/yr
Conclusion	Least unmet load and capacity storage but higher costs	Chosen configuration due to significantly reduced cost despite unmet load trade-off

System Description cont'd

- As global energy demand continues to increase, the oil and gas industry ironically continues to suspend, orphan, and abandon oil wells at an alarming rate due to technical, policy, and environmental reasons [16].

- The increasing demand to reduce the energy footprint of producing wells is compounded by the leakage of methane and other potent greenhouse gases from idle and inactive wells [17].

- The Canadian province of Alberta has historically been one of the largest oil producers in Canada. Still, the province's upstream oil and gas sector reportedly contributed substantial methane emissions, accounting for approximately 70% of Alberta's emissions in 2014 [18].

- Registered wells ~ 470,000 wells [19]
- Inactive wells ~ 155,000 wells [20]
- Suspended wells ~ 81,000 wells [20]

- Clean-up in Canada is estimated to reach $1.1 billion by 2025 [21]

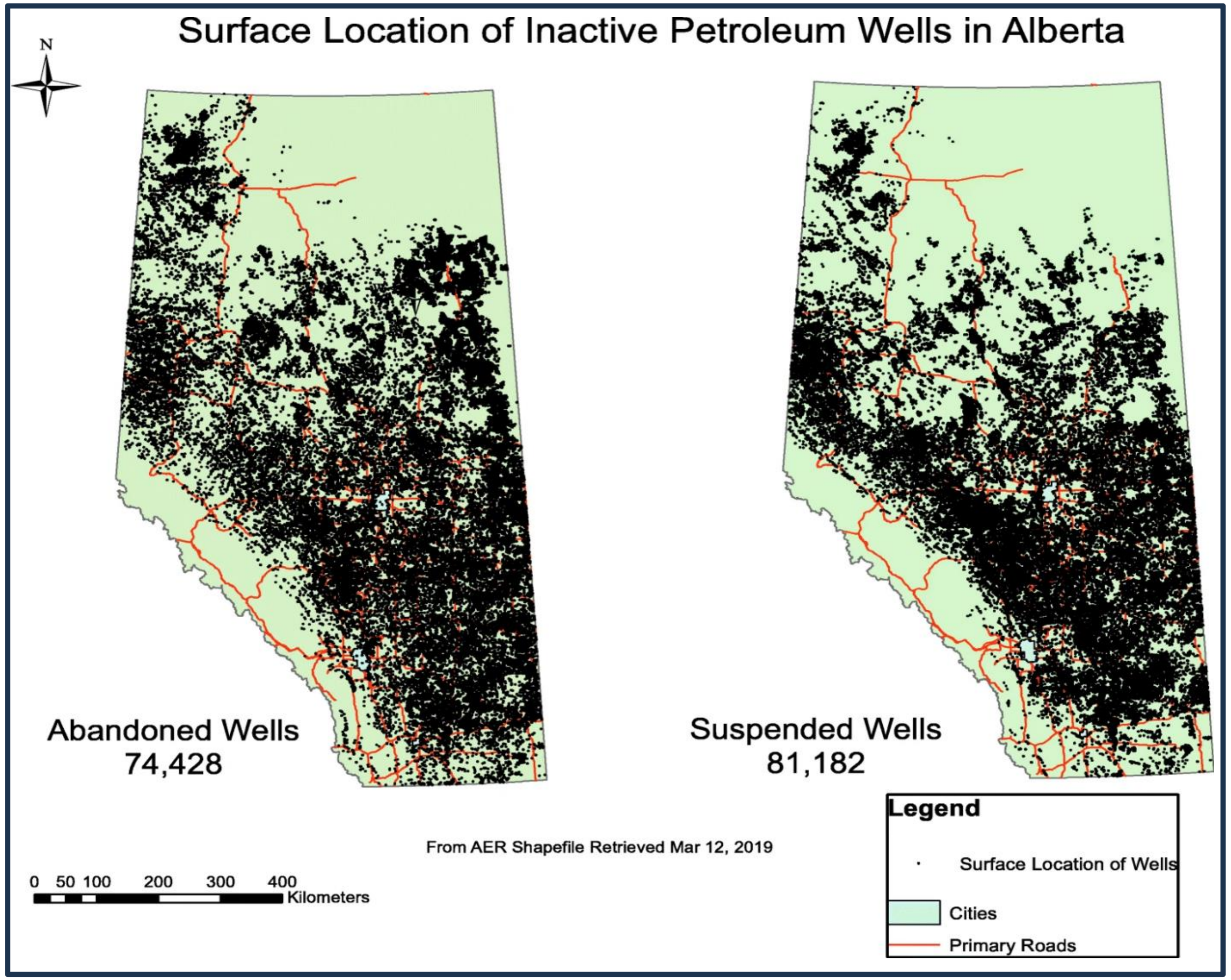


Fig 42 Surface location of inactive petroleum wells in Alberta, Canada [8].

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Methodology for Modelling sucker rod pump in SolidWorks and Simscape : Subsurface + Surface System

- The surface pump model is first developed in SolidWorks and then converted to Simscape, the rating of the pump is then implemented as a load in the solar-powered electrical microgrid.

- The model seamlessly integrates the mechanical and electrical systems with 100% renewable energy to power the sucker rod pump system.

- the SolidWorks assembly is developed and then exported to an XML file and the corresponding geometry files using the plugin

- The XML file is then imported into MATLAB/Simulink to create a Simscape multibody model

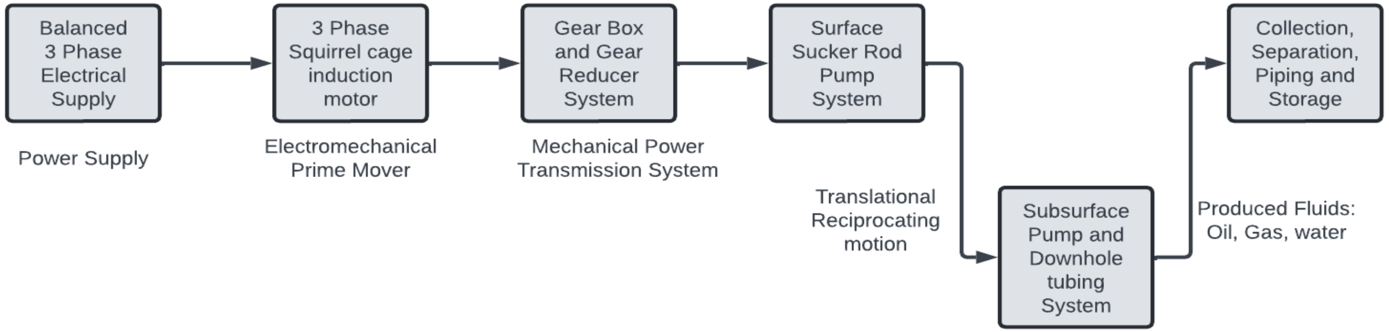


Fig. 43 Beam pump system operation and process workflow.

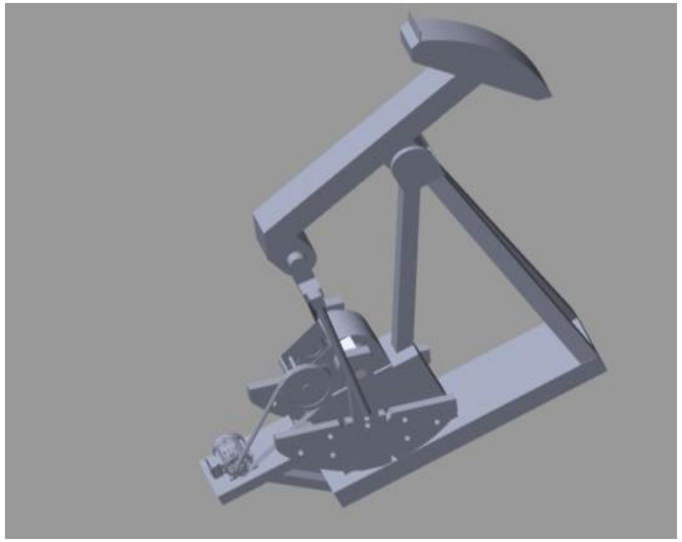


Fig 44 CAD Simulation of Surface Unit.

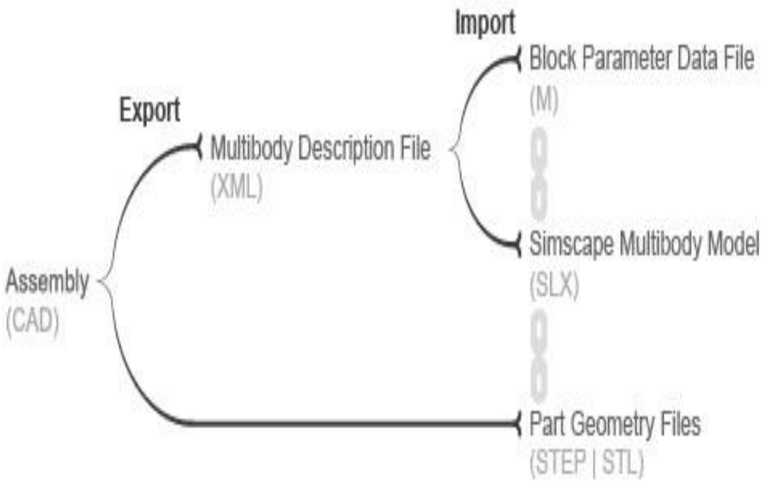


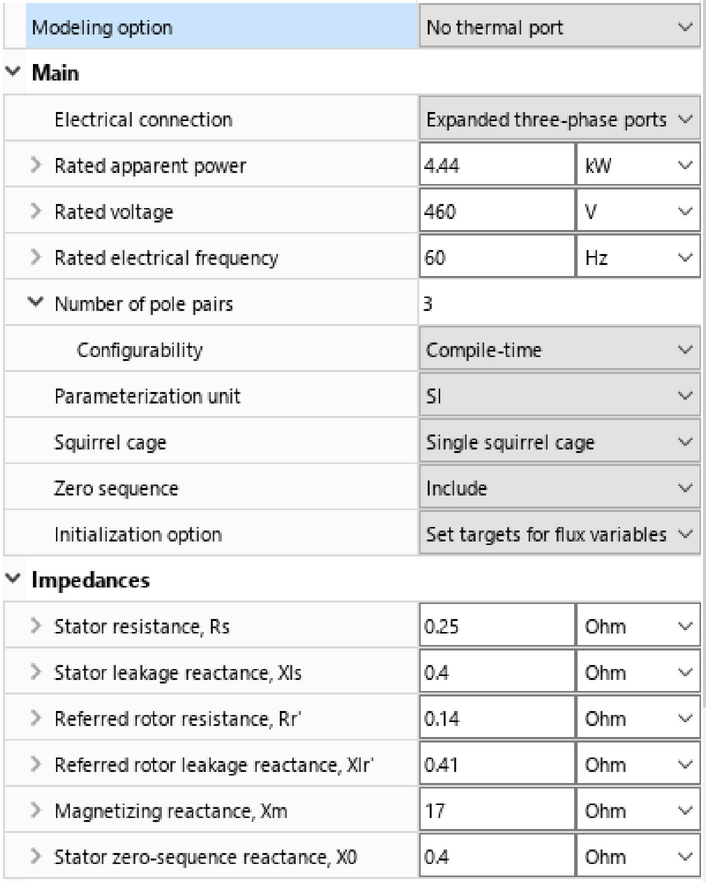
Fig 45 Converting CAD to Simscape Model [15].

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Squirrel cage induction Motor in Simscape

- The induction motor was modeled first in Simscape electrical and then modeled again to simulate integration with the overall circuit in Simscape Power systems

- The initial parametrization of the induction motor has been included in Figure 47 based on a previous work by the authors in



Modeling option	No thermal port	
Main		
Electrical connection	Expanded three-phase ports	
Rated apparent power	4.44	kW
Rated voltage	460	V
Rated electrical frequency	60	Hz
Number of pole pairs	3	
Configurability	Compile-time	
Parameterization unit	SI	
Squirrel cage	Single squirrel cage	
Zero sequence	Include	
Initialization option	Set targets for flux variables	
Impedances		
Stator resistance, Rs	0.25	Ohm
Stator leakage reactance, Xls	0.4	Ohm
Referred rotor resistance, Rr'	0.14	Ohm
Referred rotor leakage reactance, Xlr'	0.41	Ohm
Magnetizing reactance, Xm	17	Ohm
Stator zero-sequence reactance, X0	0.4	Ohm

Fig 46 Equivalent Circuit Parameters

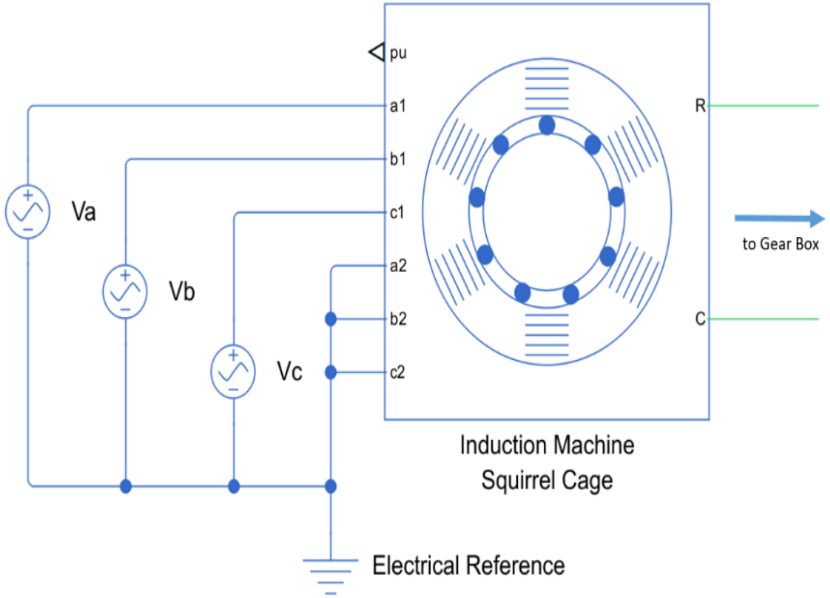


Fig 47 Three-Phase Electric Motor in Simscape.

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Surface System Modelling : Surface Pump Model

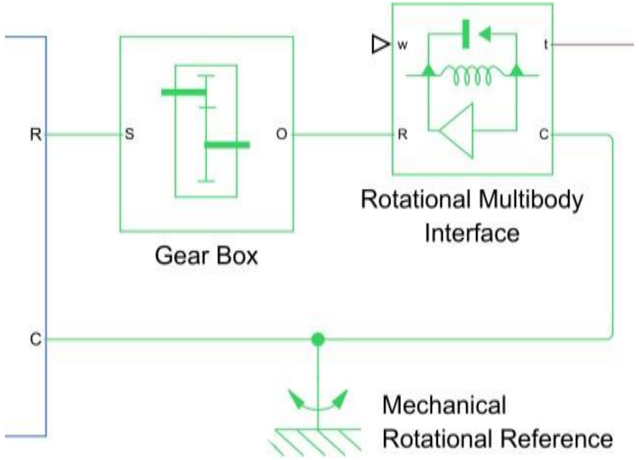

Fig 48 Gearbox and Gear reducer system

Speed of Output Shaft = Speed of input Shaft / Gear Ratio

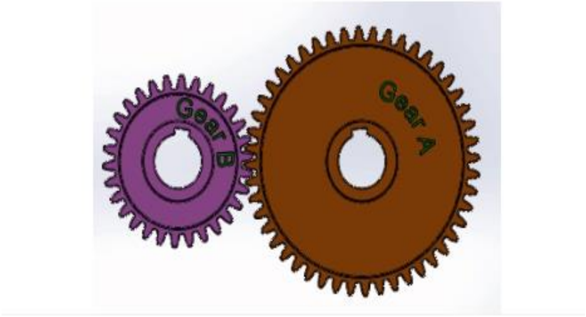

Fig 49 Gear Reduction

$$Gear\ ratio = \frac{\omega_1}{\omega_2} = \frac{n_1}{n_2} = \frac{d_1}{d_2} = \frac{T_1}{T_2}$$

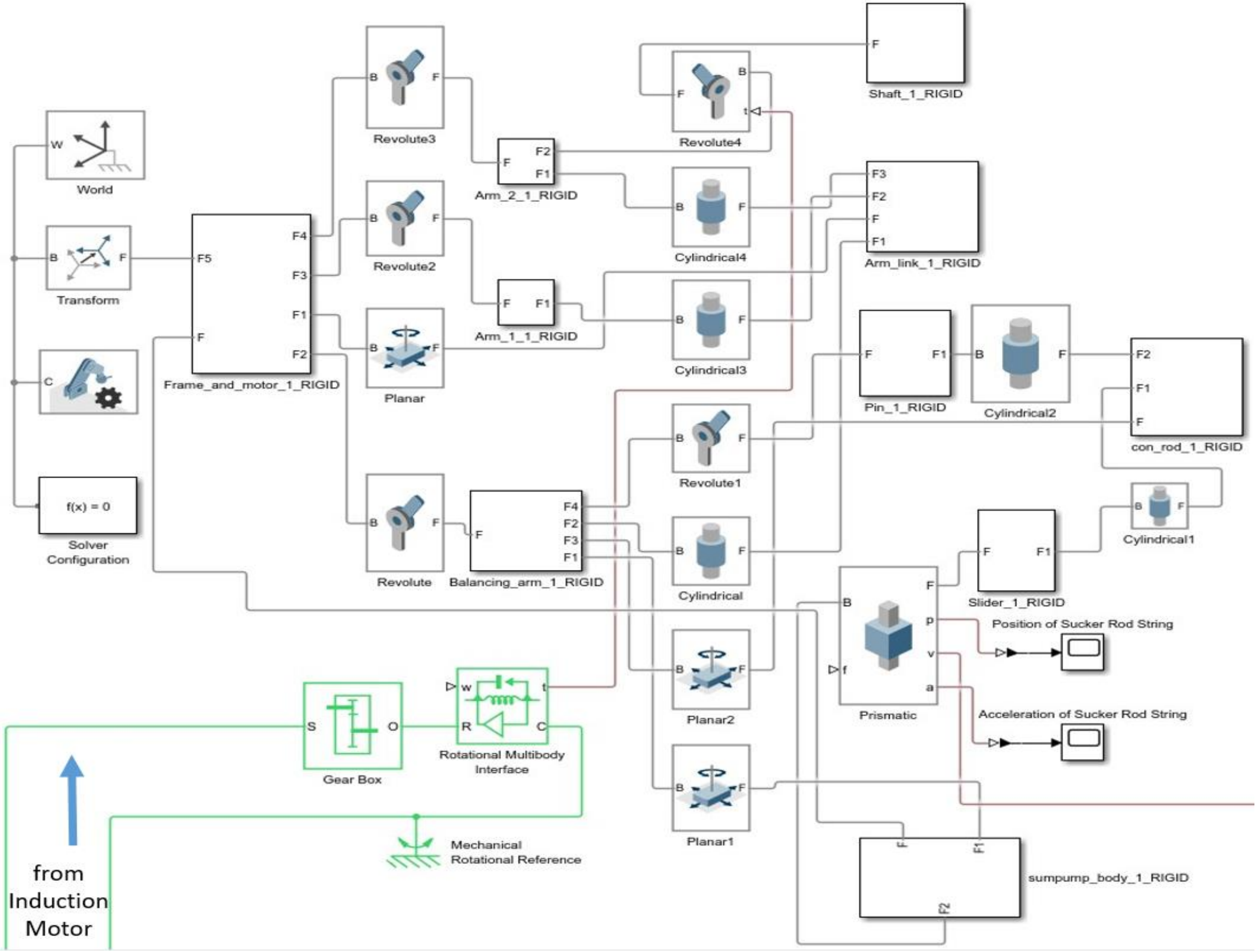

Fig 50 Model of Surface pumping unit (connected to Gearbox and Gear reducer system).

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Subsurface System Modelling : Downhole Pump

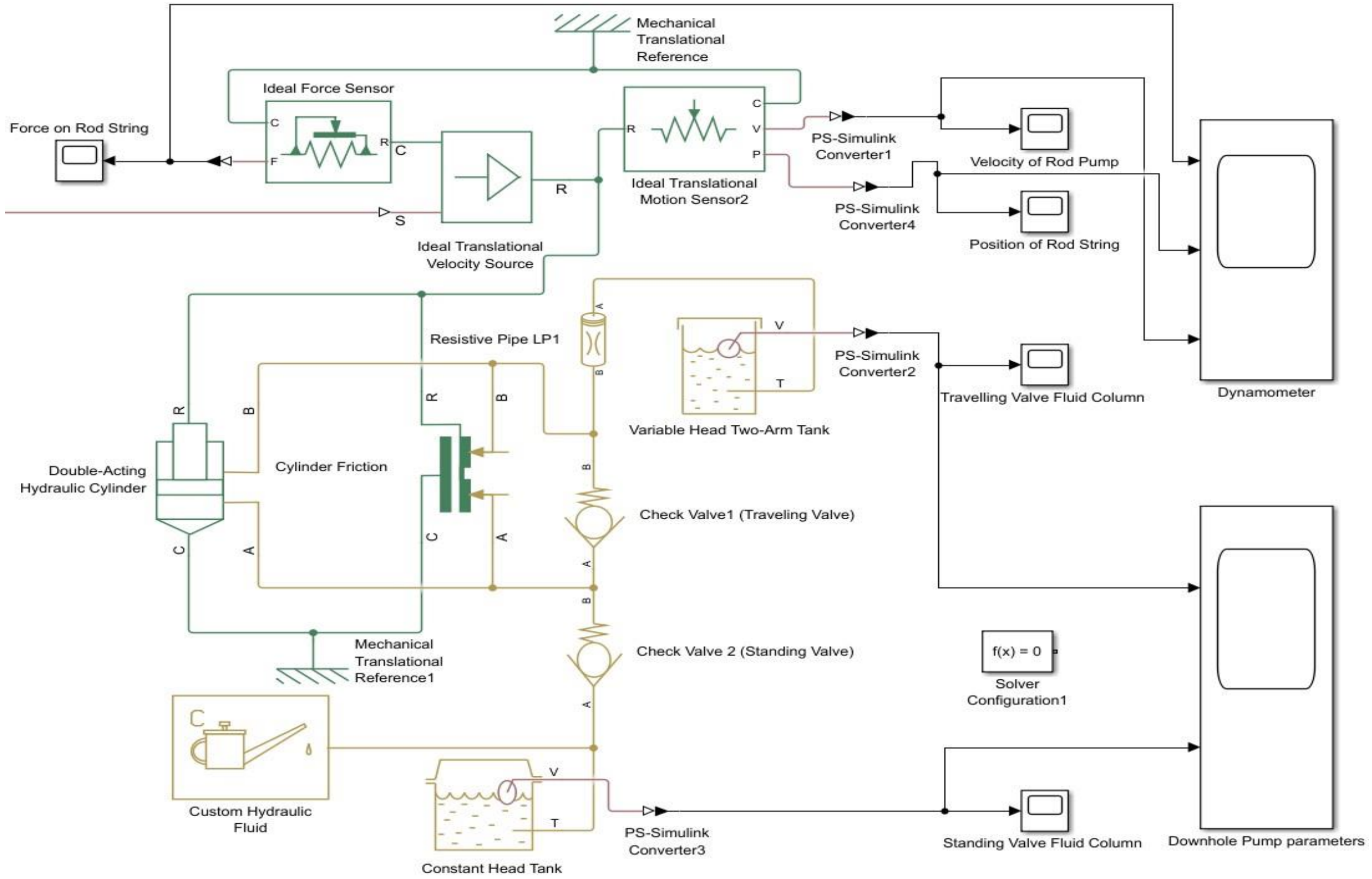

Fig 51 Model of Submerged Pump Barrel Assembly

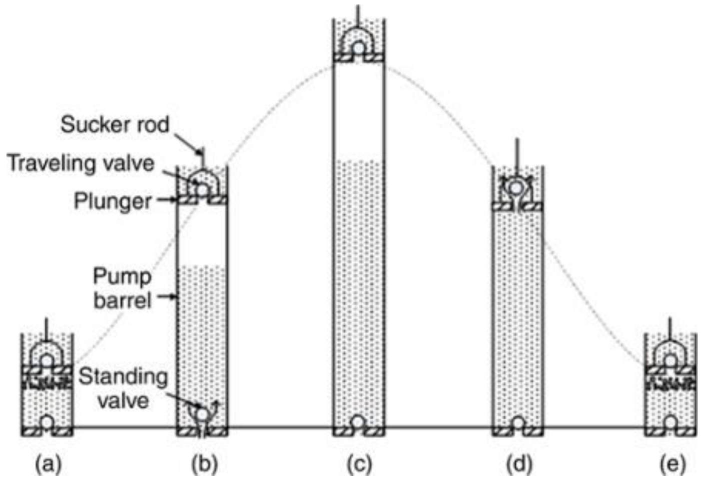

Fig 52a The pump stroke cycle of the downhole pump.

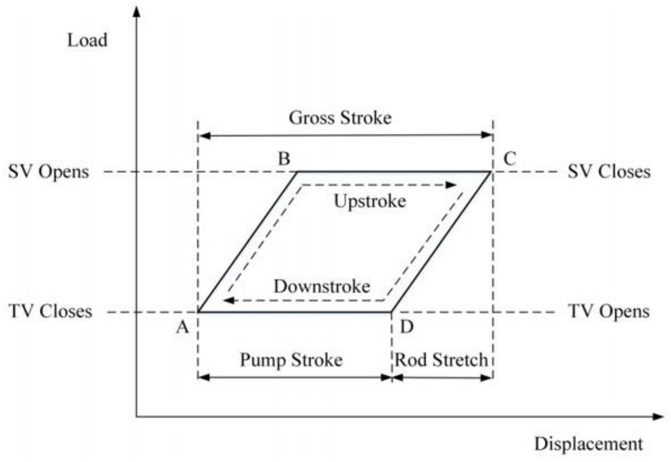

Fig 52b Load/displacement dynamics.

During the upstroke, the standing valve opens as the plunger moves up, creating a pressure differential that allows fluid to enter the pump barrel from the reservoir. Simultaneously, the traveling valve closes, allowing the fluid above it to be lifted towards the surface. On the downstroke, the standing valve closes to prevent fluid from flowing back into the reservoir. The traveling valve opens, allowing fluid to pass through the plunger, positioning it for the next upstroke[14] .

This operation closely mirrors the actual functioning of sucker rod pumps as described in the literature

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Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modeling : Solar System Components

- Intermittent pumping with solar PV and battery system will be the chosen configuration for further design in this research
- Because considering production from inactive oil wells (suspended and idle), the unmet load for the solar PV and battery system can be suitably accommodated in the pumping schedule as a trade-off to the significantly reduced cost in comparison to the solar PV, wind and battery storage system.
- Hence the solar PV and battery system would be adopted for powering the remote oil well.
- The system comprises a 27.3kW Solar PV array, and battery bank, comprising 64 units of deep cycle batteries, of 16 strings and 4 batteries per string.
- A system converter rated 4.49 kW, and a load dispatch of cycle charging is implemented, implying that the primary load (electric motor) receives supply first and the excess generation goes to charge the battery bank.

Table 8 Solar microgrid source.

Component	Name	Size
PV	Jinko eagle PERC60	27.3 kW
Storage	Deep cycle batteries, SAGM (12 V, 219Ah)	64 units (16 strings)
System converter	Schneider (Conext XW + 548)	4.49 KW
Dispatch	Cycle charging	

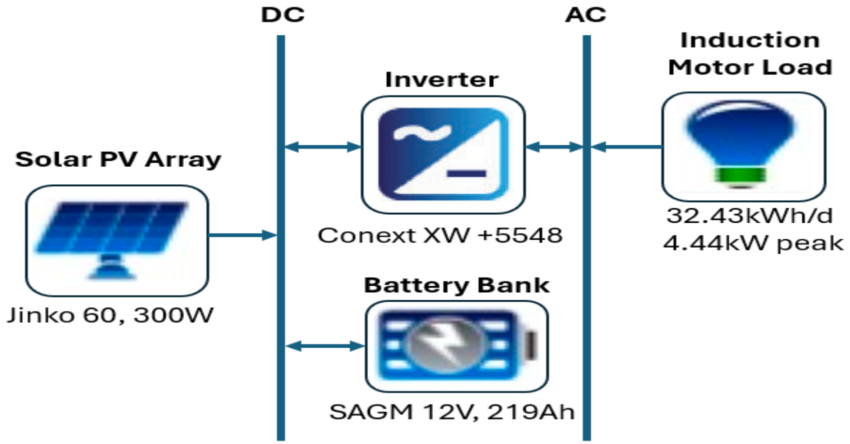

Fig 53 Schematic diagram of the proposed system.

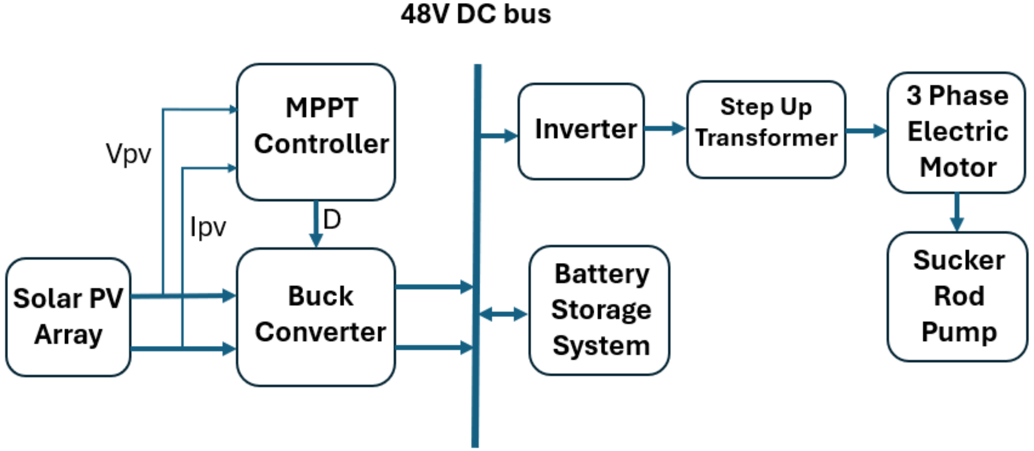

Fig. 54 Block Diagram of proposed Solar PV microgrid.

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Environmental conditions such as solar irradiance and ambient temperature for summer and winter are obtained from data repositories and included in the modelling and analysis of the overall system performance demonstrating stable operation.

Table 9 Average Solar Irradiance and Temperature Data for winter at Medicine Hat [33] [34].

Time (Hrs)	Irr (W/m^2)	Temp (Deg. C)
1	0	−7
2	0	−8
3	162	−8
4	752	−8
5	1239	−7
6	1548	−6
7	1657	−6
8	1558	−5
9	1260	−6
10	781	−7
11	198	−8
12	0	−9

Table 10 Average Solar Irradiance and Temperature Data for summer at Medicine Hat [33] [35].

Time (Hrs)	Irr (W/m^2)	Temp (Deg. C)
1	0	10
2	138	10
3	785	10
4	1513	12
5	2236	15
6	2904	19
7	3472	22
8	3900	23
9	4160	25
10	4234	25
11	4117	25
12	3817	27
13	3354	27
14	2760	27
15	2075	27
16	1347	27
17	624	26
18	60	24
19	0	21

- Open-source Canadian Weather Energy and Engineering Climate (CWEC) data [34] for Average Hourly Irradiance
- Hourly historical data report per month is also available from the Environment and Climate Change Canada website [35][36]

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Hourly Solar Irradiance and Temperature Data

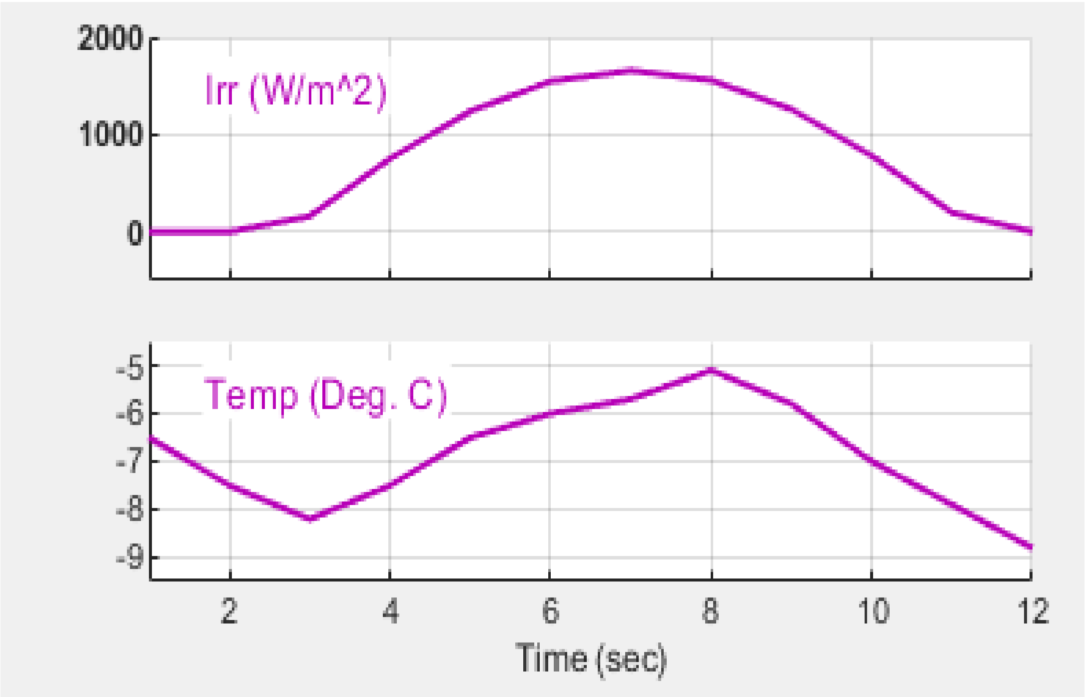

Fig 55a Sample Winter Data (January).

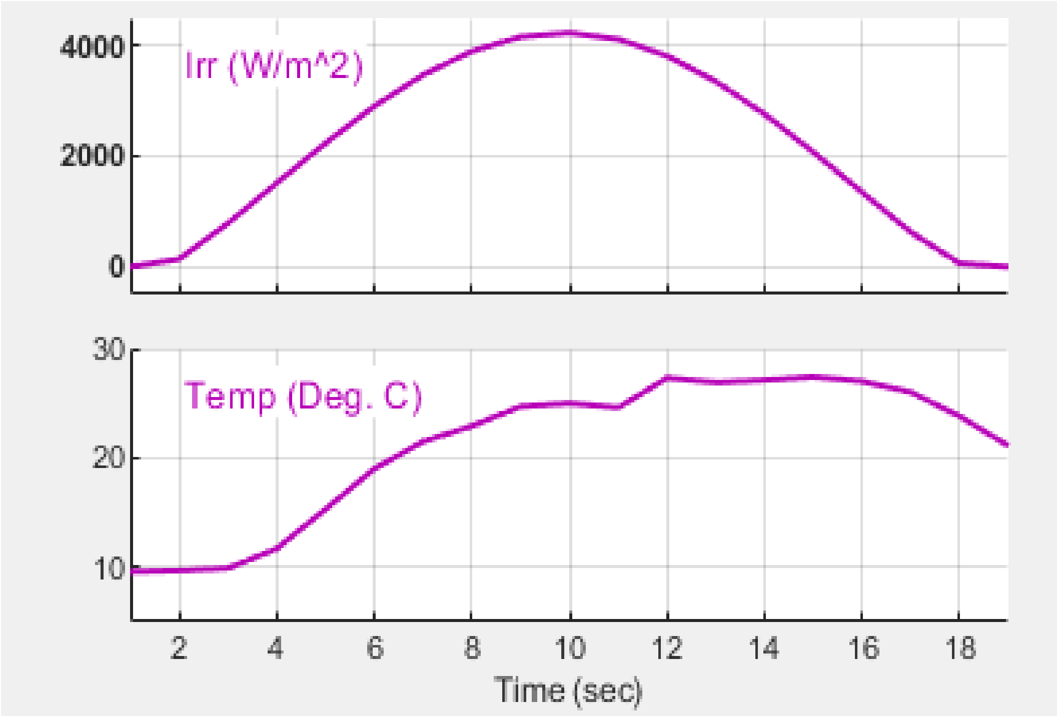

Fig 55b Sample Summer Data (June).

Sample average daily solar irradiance and temperature data for Medicine Hat for winter and summer respectively.

- scaling the data accordingly for 1 h ≡ 1 s for simulation, we can infer that there is significantly higher average hourly irradiance and correspondingly higher temperatures for the chosen location in the summer months than in winter.

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Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Solar PV System Parameters

Table 11 Solar PV System Parameters

System parameters	Ratings	Unit
Module peak power of a single module (P_{mp})	300.25	W
Module open circuit voltage (V_{oc})	40.1	V
Module short circuit current (I_{sc})	9.72	A
Module voltage at MPP (V_{mp})	32.6	V
Module current at MPP (I_{mp})	9.21	A
Array peak power (P_{mp})	27.6	kW
Array open circuit voltage (V_{oc})	80.2	V
Array short circuit current (I_{sc})	447.12	A
Array voltage at MPP (V_{mp})	65.2	V
Array current at MPP (I_{mp})	423.66	A

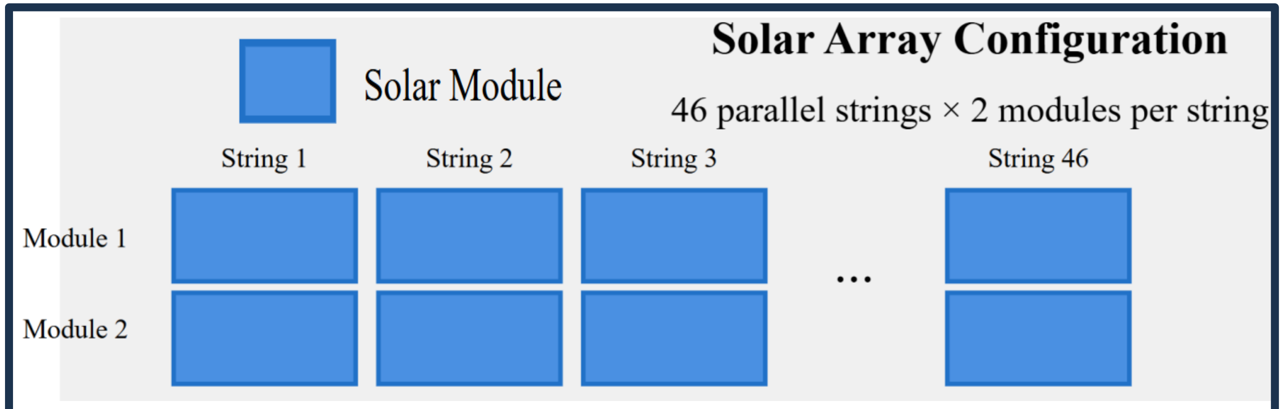

Fig 56a Solar PV array configuration.

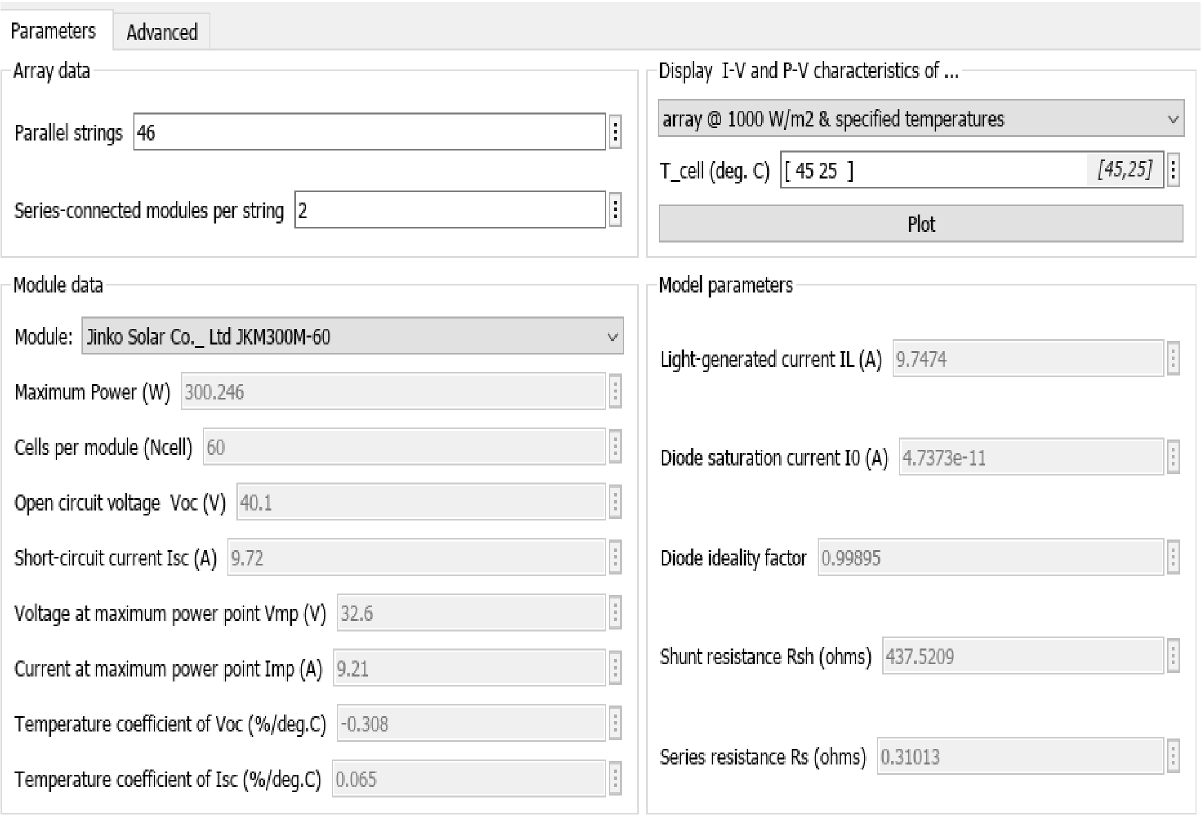

Fig 56b Solar PV array design specifications for modelling.

$$P_{mpp} = (\ N_p \times I_{mpp}) \times (N_s \times V_{mpp}) = (46 \times 9.21) \times (2 \times 32.6) \approx 27.6kW$$

$$= Total\ Number\ of\ modules \times Maximum\ Power\ per\ module$$

$$= 46\ parallel\ strings \times 2\ modules\ per\ string \times 300.246\ W \approx 27.6kW$$

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Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : DC-Dc Buck Converter Parameters

Table 12 DC-Dc Buck Converter Parameters

System parameters	Ratings	Unit
Input voltage at MPPT (V_{in})	66	V
Frequency (f)	5	kHz
Buck inductance (L_{Buck})	17.32	µH
Buck capacitance (C_{Buck})	4740	µF
Output capacitance (C_{out})	5924.48	µF
Output voltage for bus (V_{out})	48	V

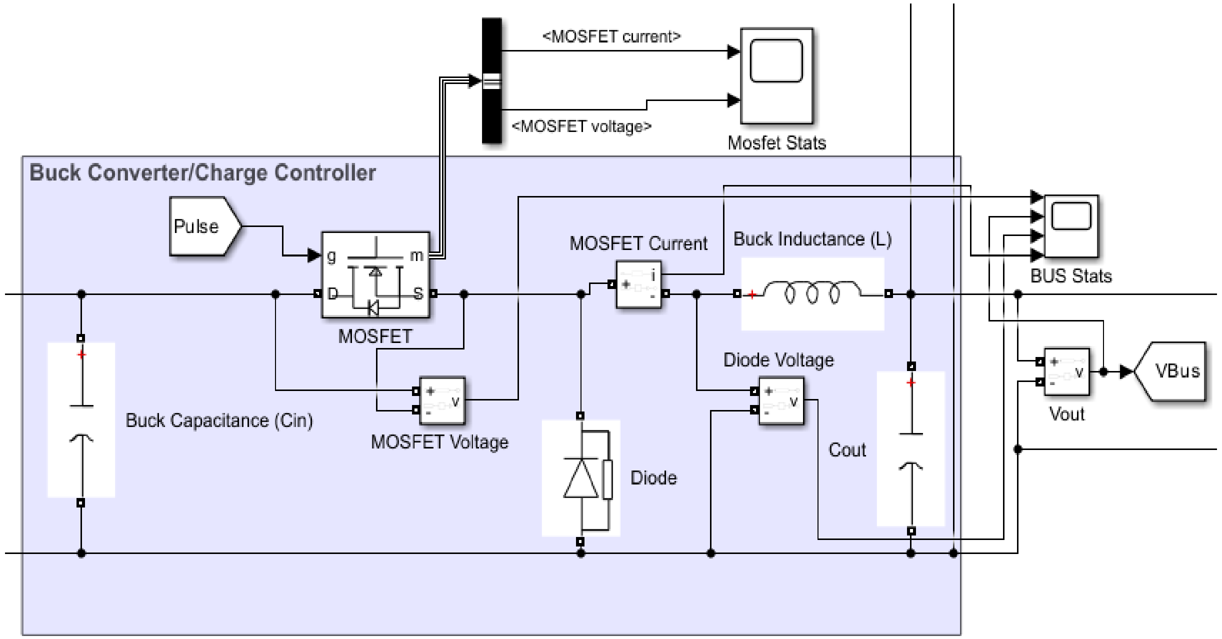

Fig 57 Equivalent circuit of Buck Converter for charge control and MPPT implementation.

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : MPPT Algorithm

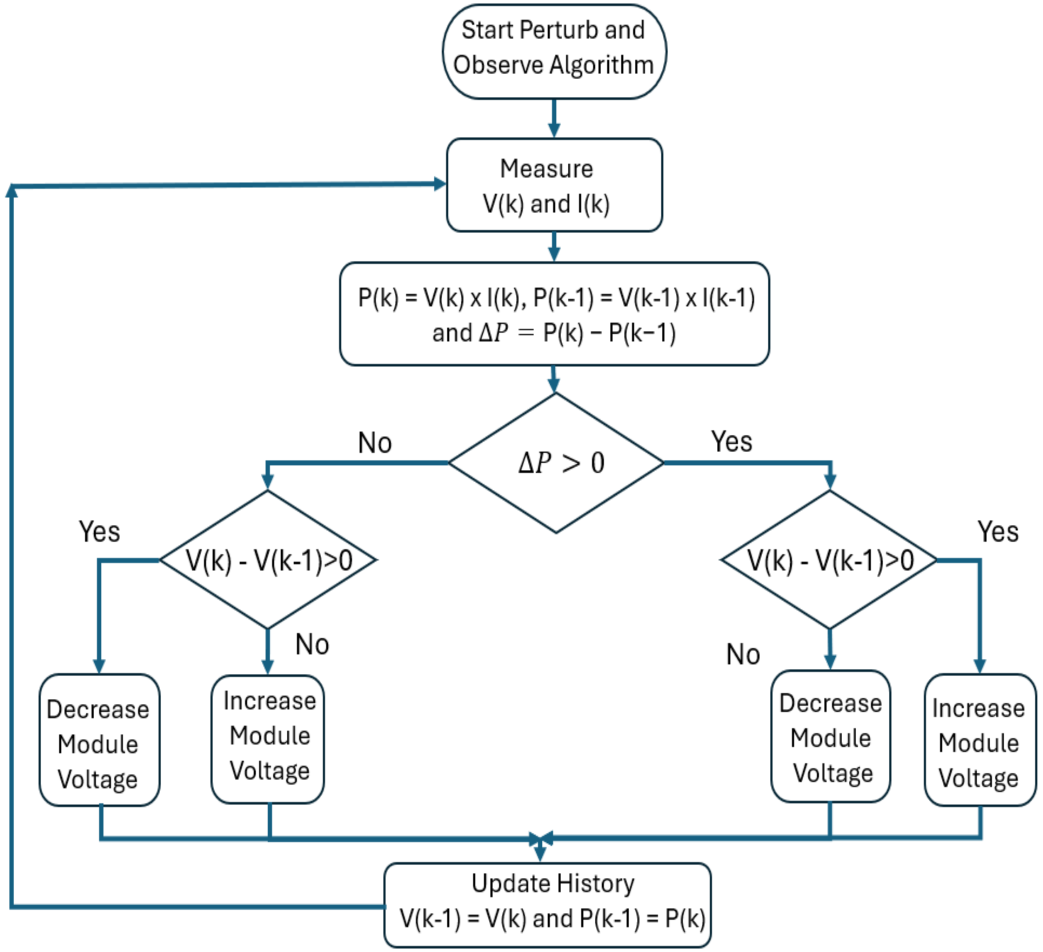

Fig 58a Flow chart and representation of Perturb and Observe (P&O) algorithm for MPPT.

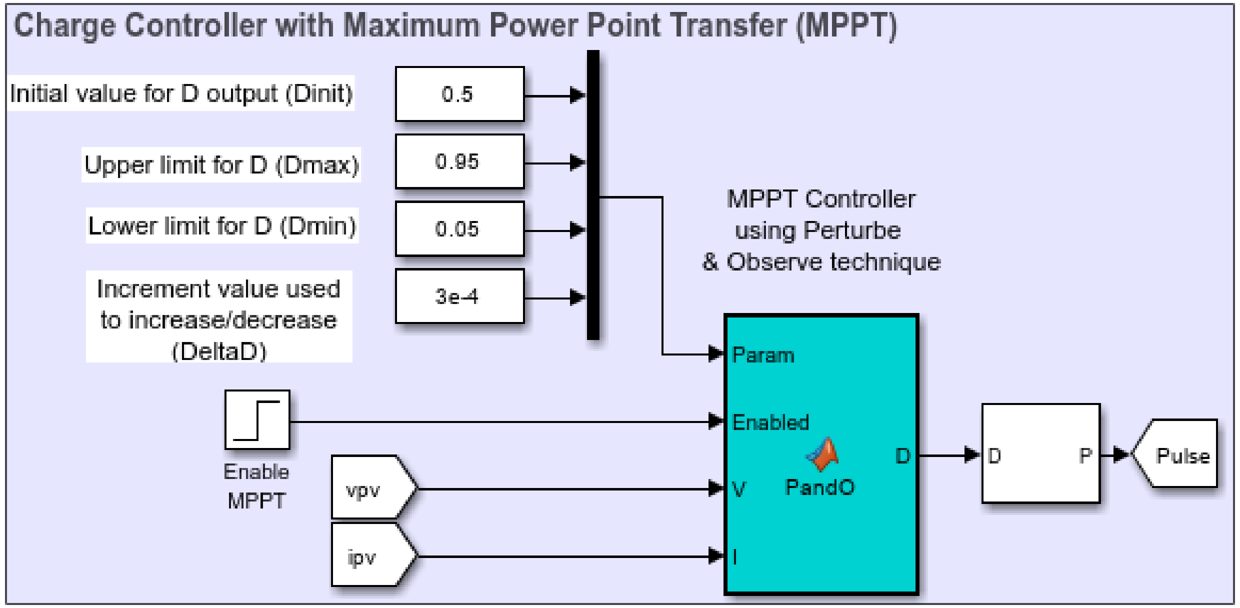

Fig 58b Perturb and Observe algorithm with MPPT Strategy in Simscape.

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Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Battery Energy Storage System Parameters

Table 13 BESS parameters.

Battery bank data	Ratings	Unit
Number	64	(4 bt/string)
Strings in parallel	16	Strings
Bus voltage	48	V
Nominal capacity	168	kWh
Usable nominal capacity	118	kWh
Energy in	3860	kWh/yr
Energy Out	3294	kWh/yr

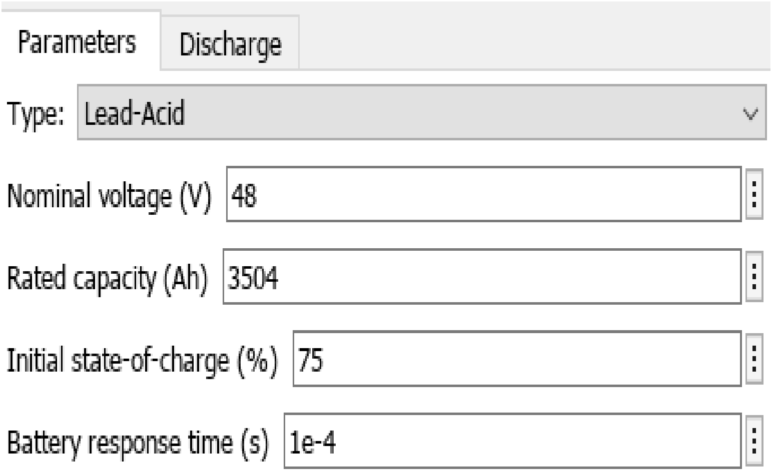

Fig 59a Design Specifications of BESS.

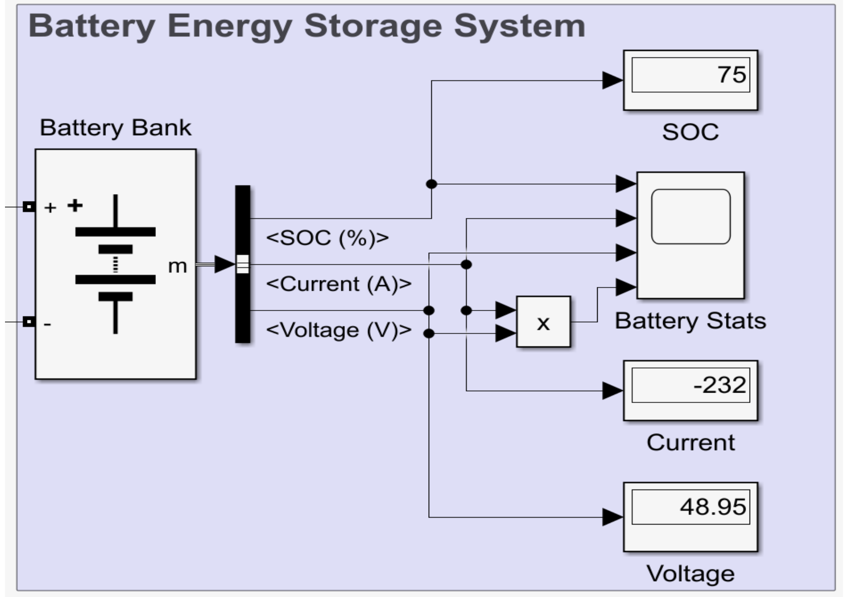

Fig 59b Equivalent circuit of Battery Energy Storage System.

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Power conditioning system parameters

Table 14 Power conditioning system parameters

Power conditioning system parameters	Ratings	Unit
Primary voltage (V_1)	30	V
Secondary voltage (V_2)	460	V
Frequency (f)	60	Hz
RMS line-to-line voltage $V_{L-L(rms)}$	33.84	V
Nominal power	7	kVA
Modulation index, m (assumed)	1	

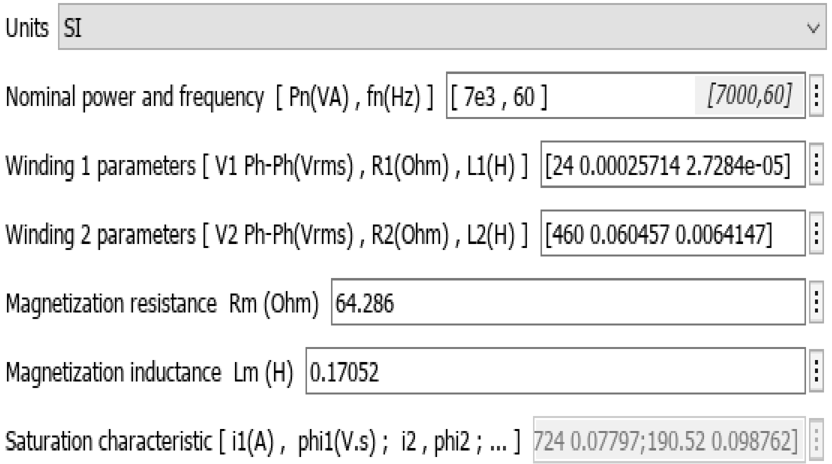

Fig 60a An equivalent circuit of a power conditioning system for the induction motor load.

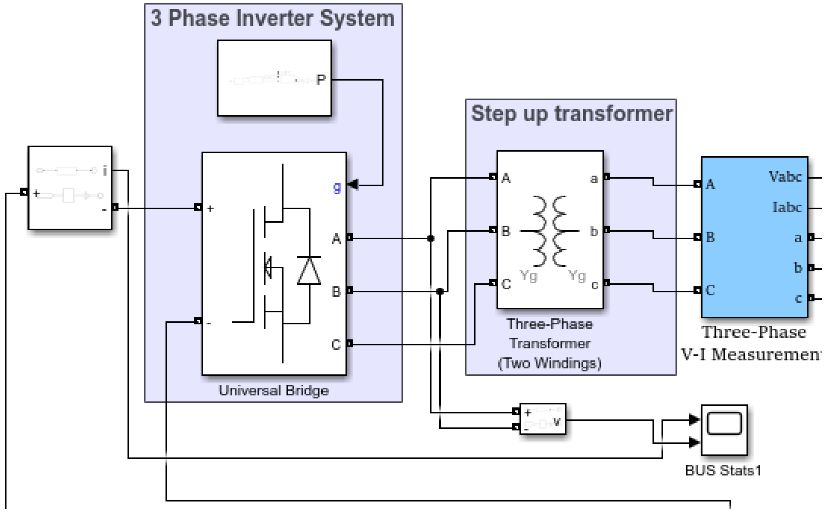

Fig 60b Equivalent circuit of a power conditioning system

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Surface System Modelling : Load Parameters

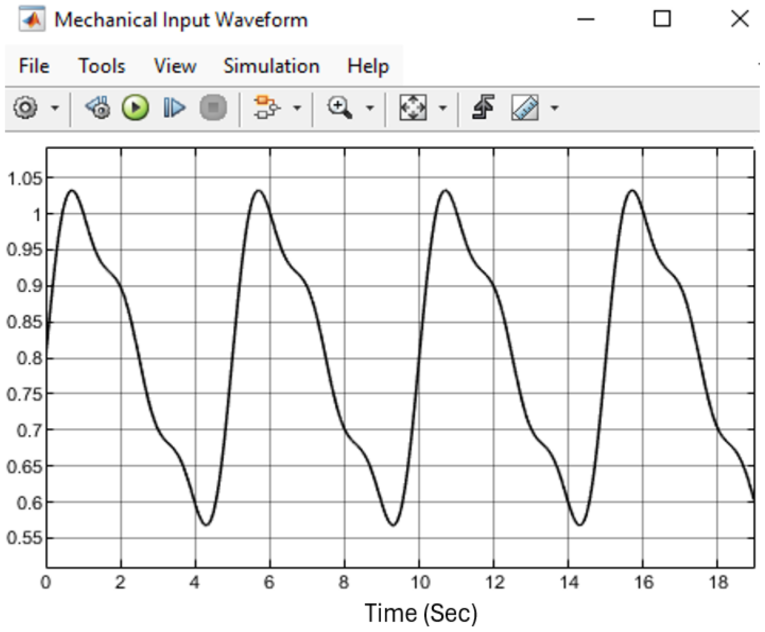

Fig 61 The waveform of mechanical torque requirement of Squirrel cage motor

Table 15 Nameplate 3-phase induction motor parameters

Motor parameters	Ratings	Unit
Line-to-line voltage	460	V
Full load current	10	A
Peak load	4.44	kW
Rated power	7.5	hp
Full load speed	1110	rpm
Full load torque	35.4	lb-ft
Efficiency	83.5	%
Power factor	0.835	
Safety factor	1.15	

The full motor parameters and nameplate data are presented in Table 15

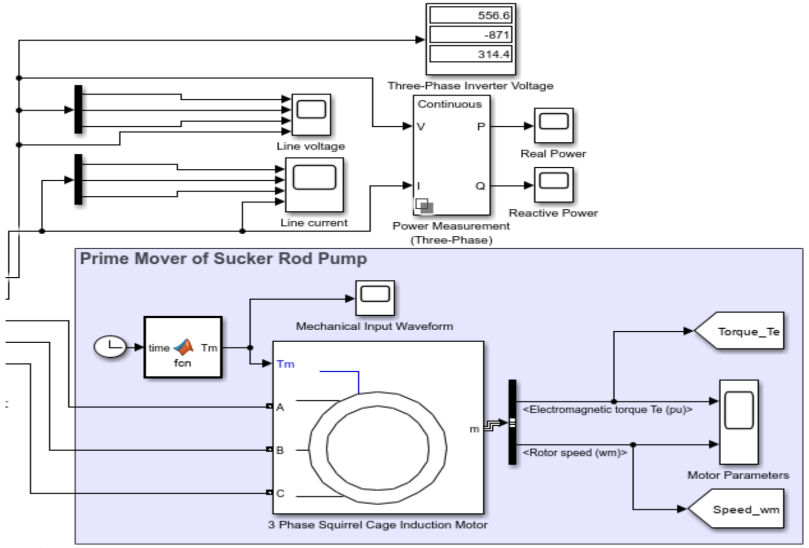

Fig 62 Equivalent circuit of the squirrel cage Induction motor prime mover.

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- Using June as a sample summer month in Medicine Hat, it is shown to have longer daytime hours and higher levels of solar irradiance, with warmer temperatures.
- In comparison with January taken as a sample winter month which is observed to have shorter hours and lower levels of solar irradiance, at lower temperatures

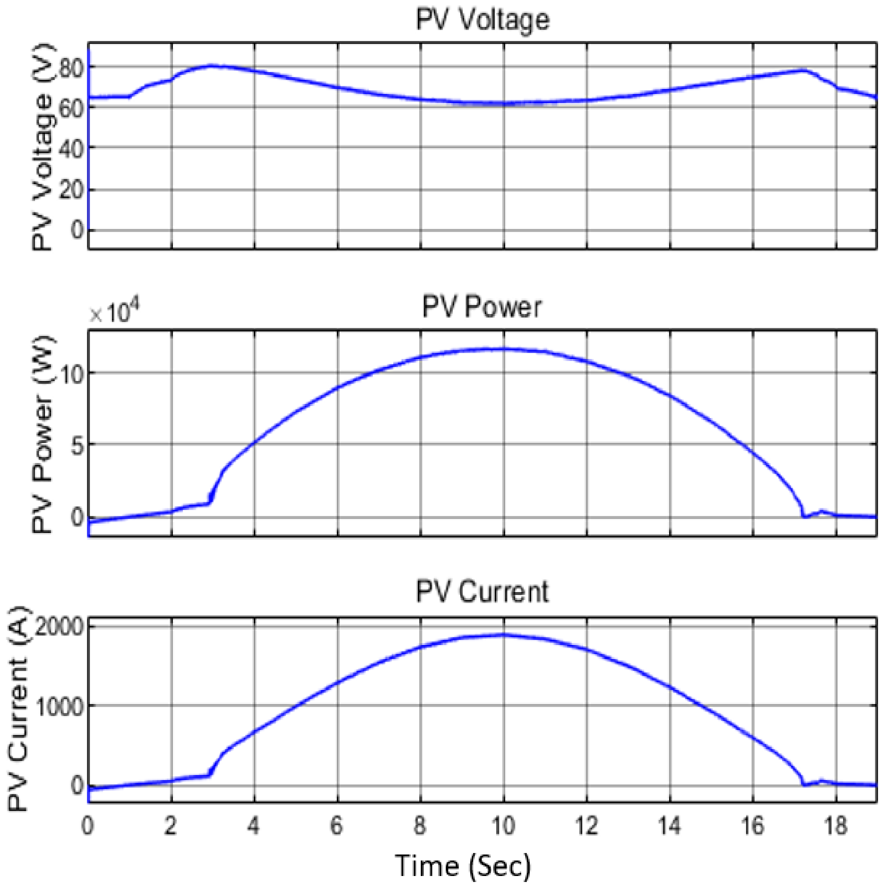

Fig 63a Summer

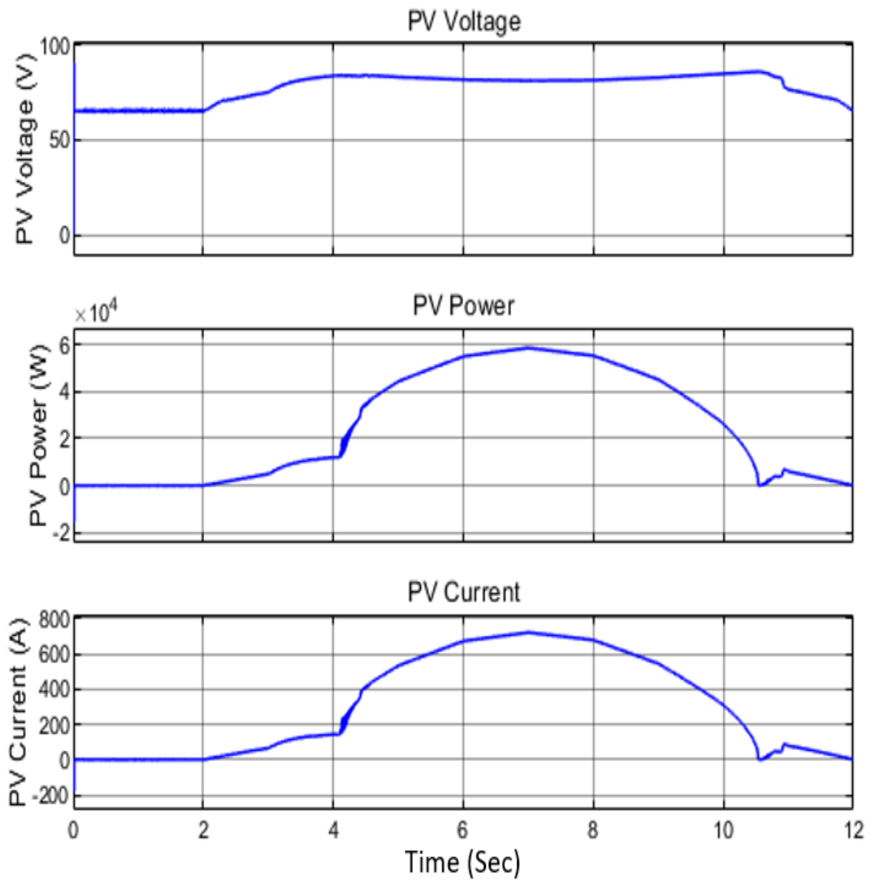

Fig 63b Winter

Fig 63 Solar PV voltage, current, and power

- The current, voltage and power of the battery energy storage system are steady, predictable and consistent with the expected behavior for steady state operation. Considering state of charge, in summer, it increases gradually from ~75% to ~90% over 19 s, while winter shows similar upward trend from ~75% to ~85% over 12 s.

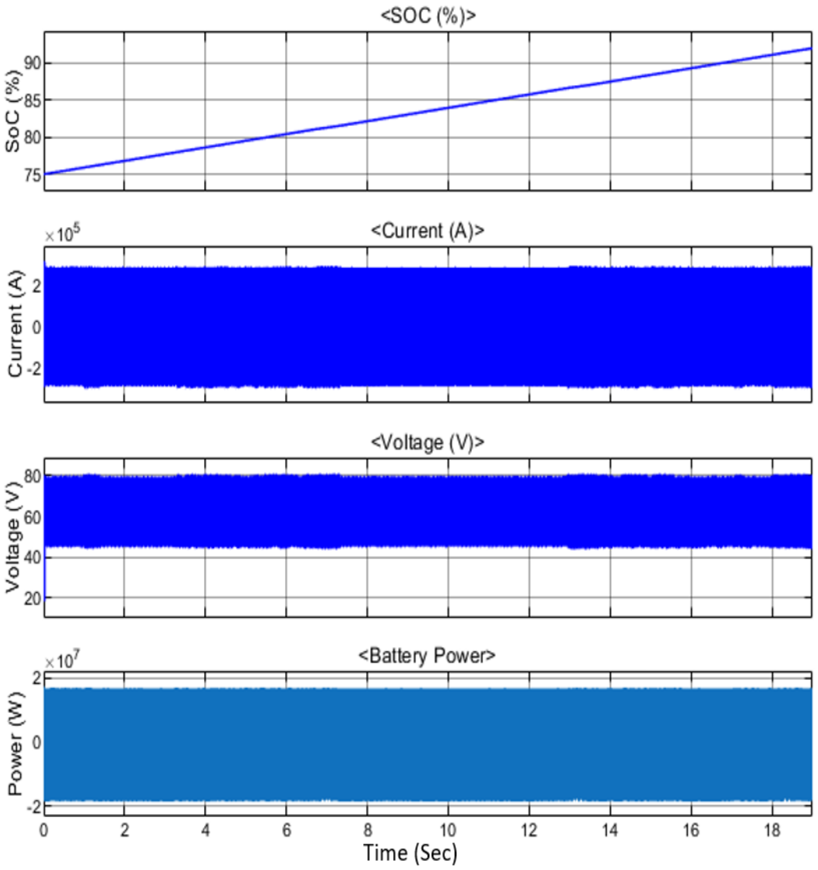

Fig 64a Summer

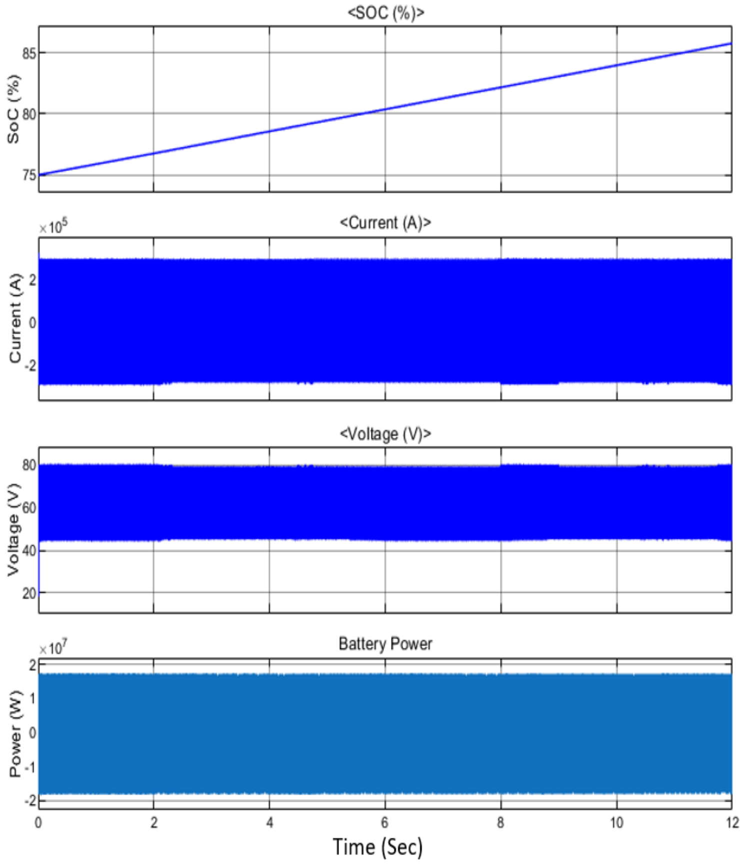

Fig 64b Winter

Fig 64 Solar PV voltage, current, and power

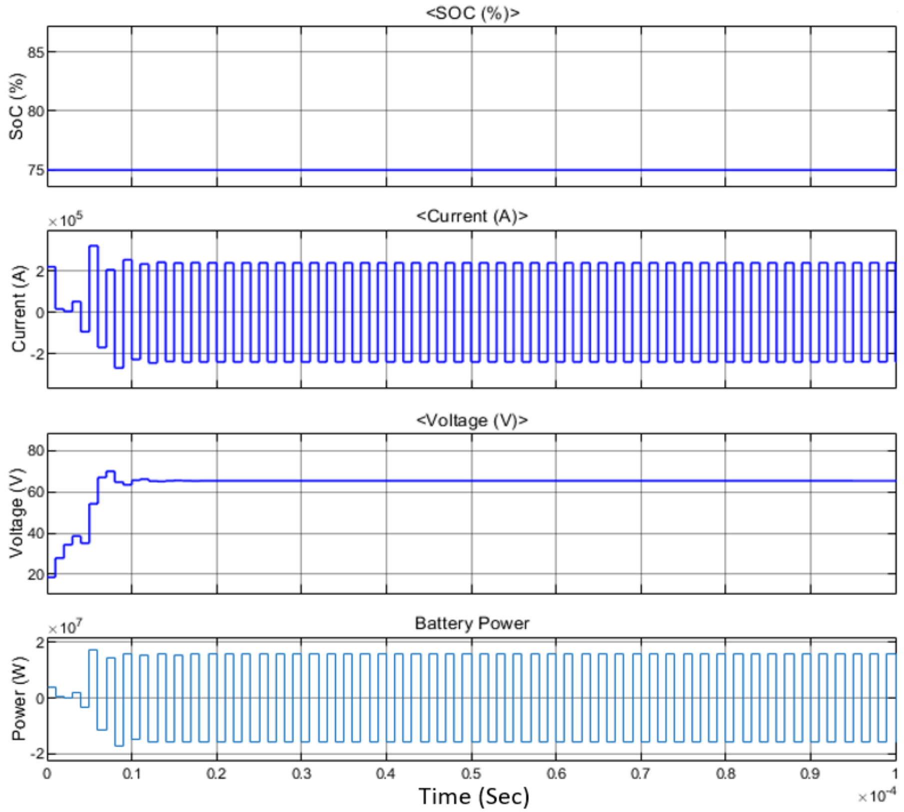

Fig 64c. Battery parameters (higher resolution)

Battery state of charge (SOC%), current, voltage, and power for battery energy storage system.

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Analysis of Results

The pulsating direct current (DC) power supply (from the solar PV system and the battery backup) is converted to alternating current (AC) by the three-phase inverter system and the sinusoidal line voltages and line currents received by the three-phase squirrel cage induction motor are given in Figure 68a,b, respectively.

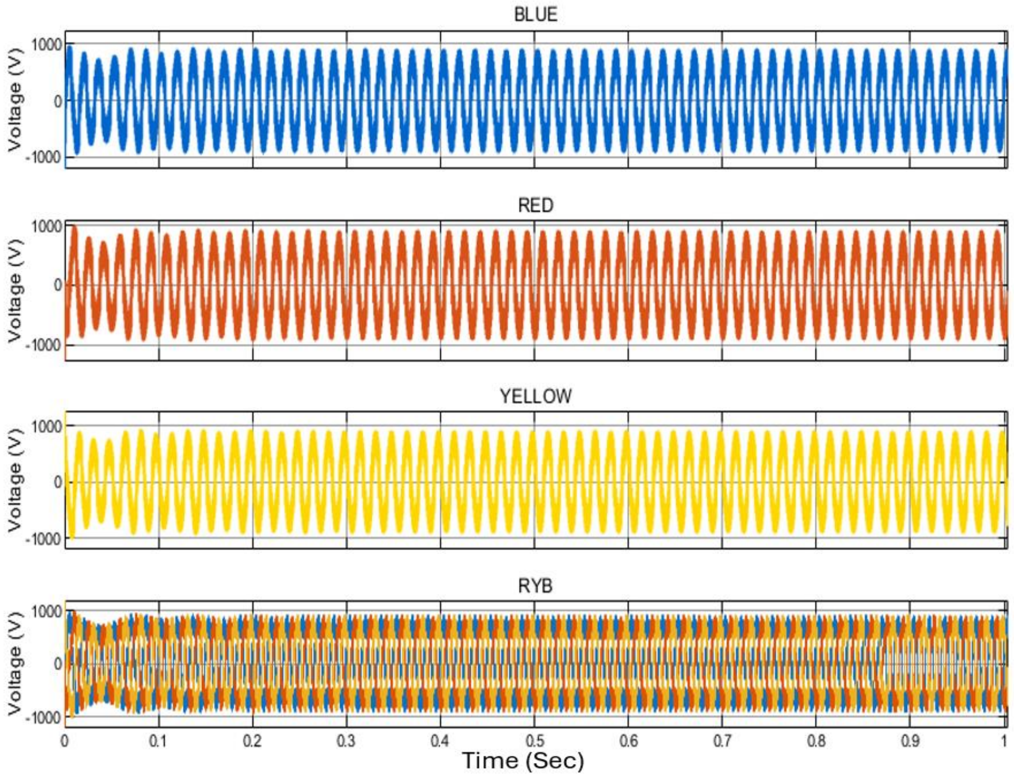

Fig 65a Sinusoidal Load Voltage V_{RYB}

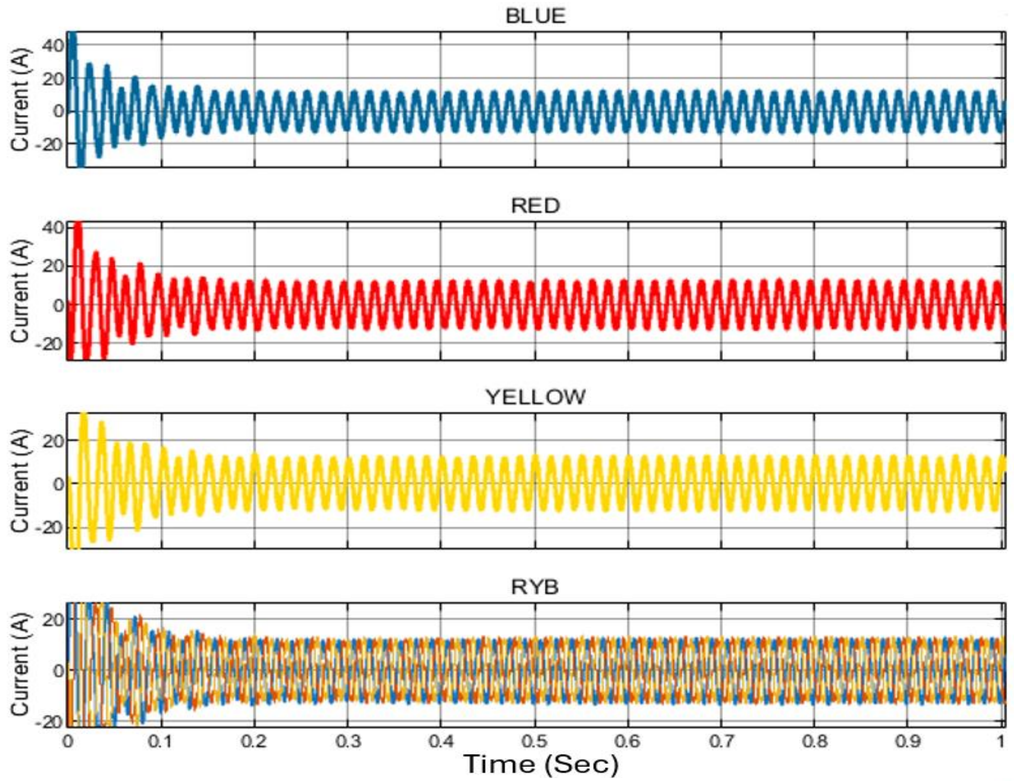

Fig. 65b Sinusoidal Load current I_{RYB}

Fig 65 Similar Sinusoidal load current and voltage I_{RYB}, V_{RYB} for summer and winter

Analysis of Results

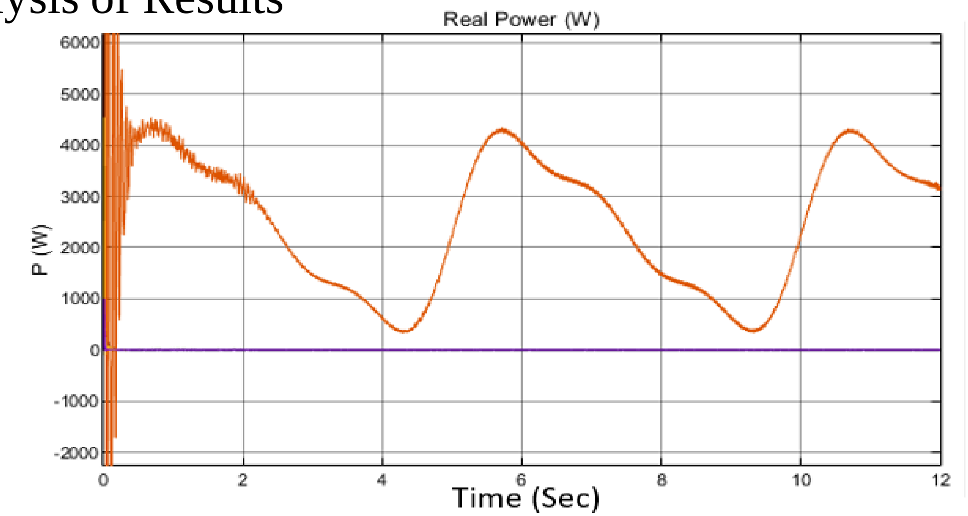

Fig 66a Real power demand

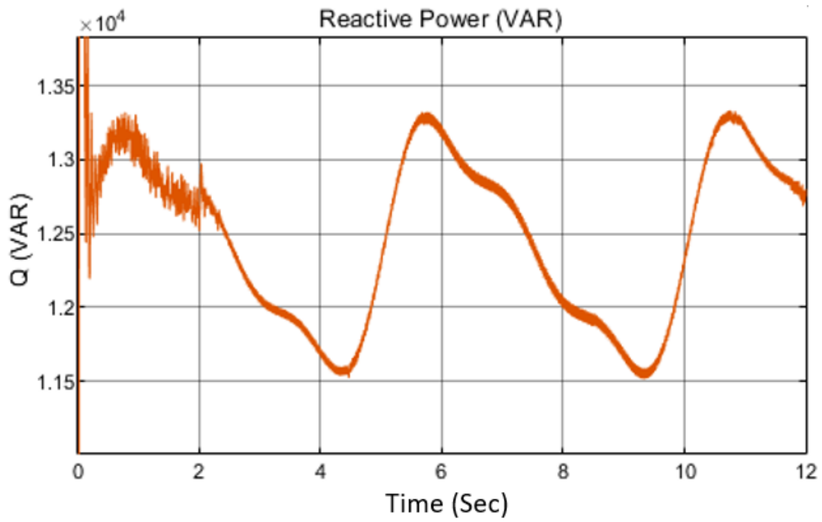

Fig 66b Reactive power demand

Fig 66 Similar real and reactive power demand for winter

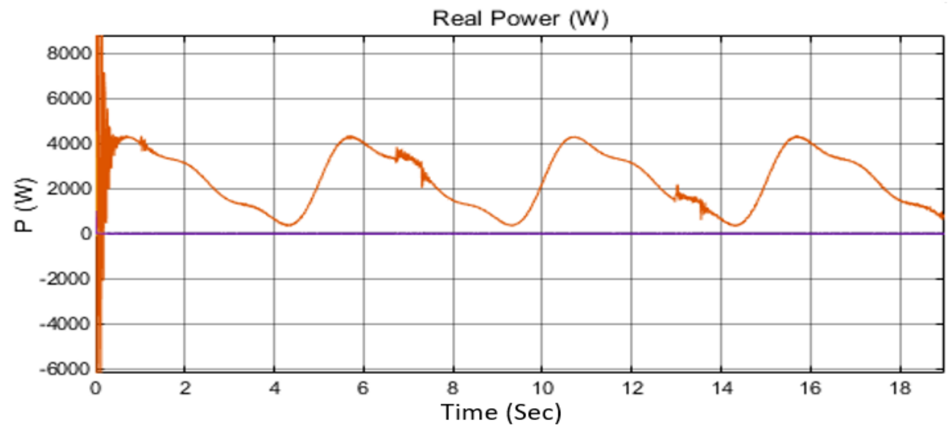

Fig. 67a. Real power demand

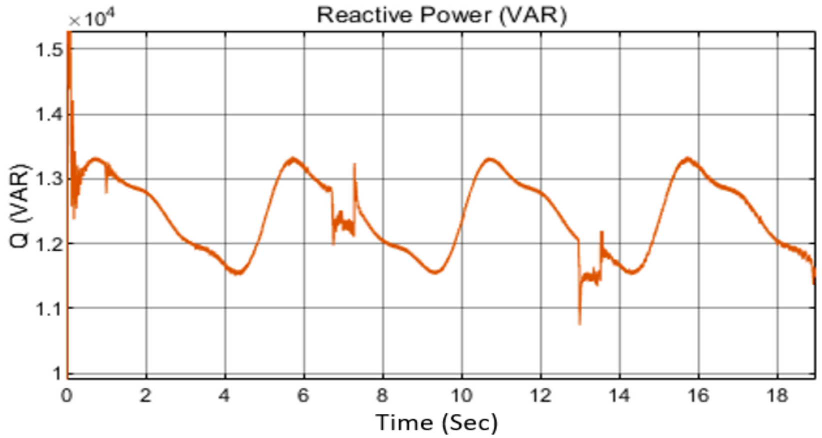

Fig. 67b. Reactive power demand

Fig 67 Similar real and reactive power demand for summer

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Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump

Analysis of Results

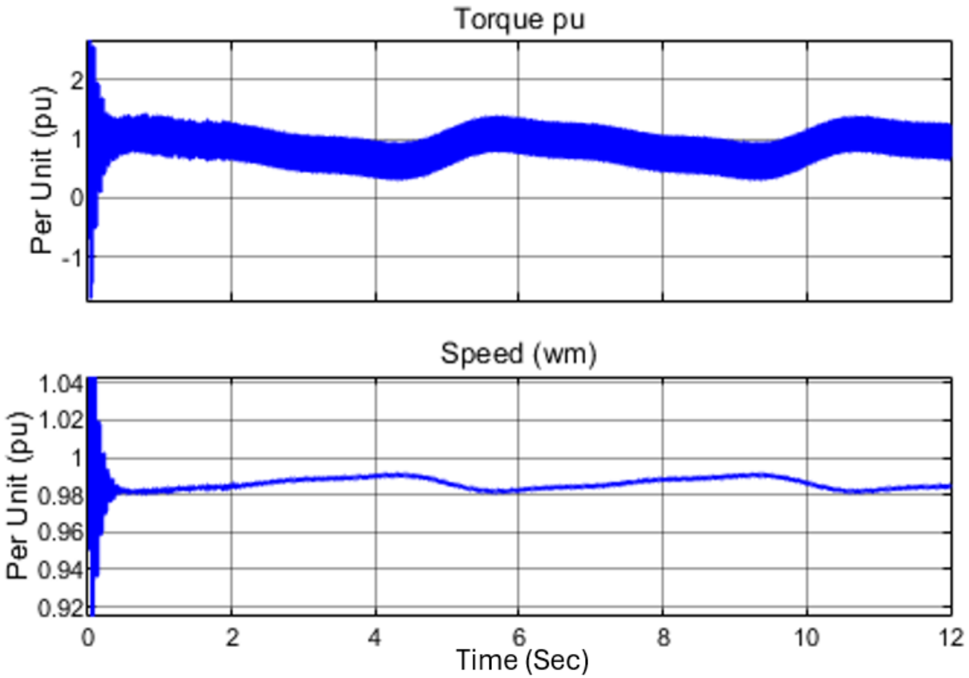

Fig 68 Similar Torque and Speed characteristics

for summer and winter

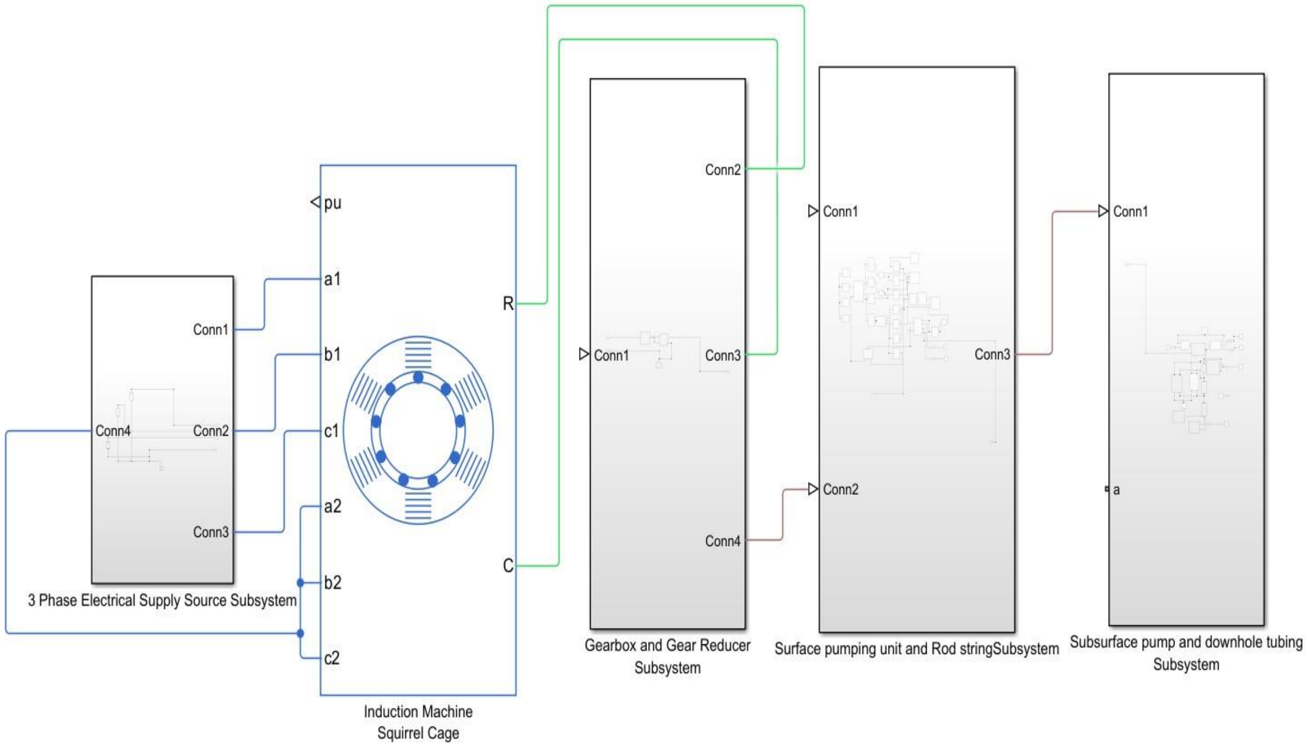

Fig 69 Schematic diagram of integrated sub-systems in model-based simulation.

Design, Dynamic Modelling, Simulation, and Control of a Solar-powered Sucker Rod Oil Pump :

Surface System Modelling : Equivalent Circuit

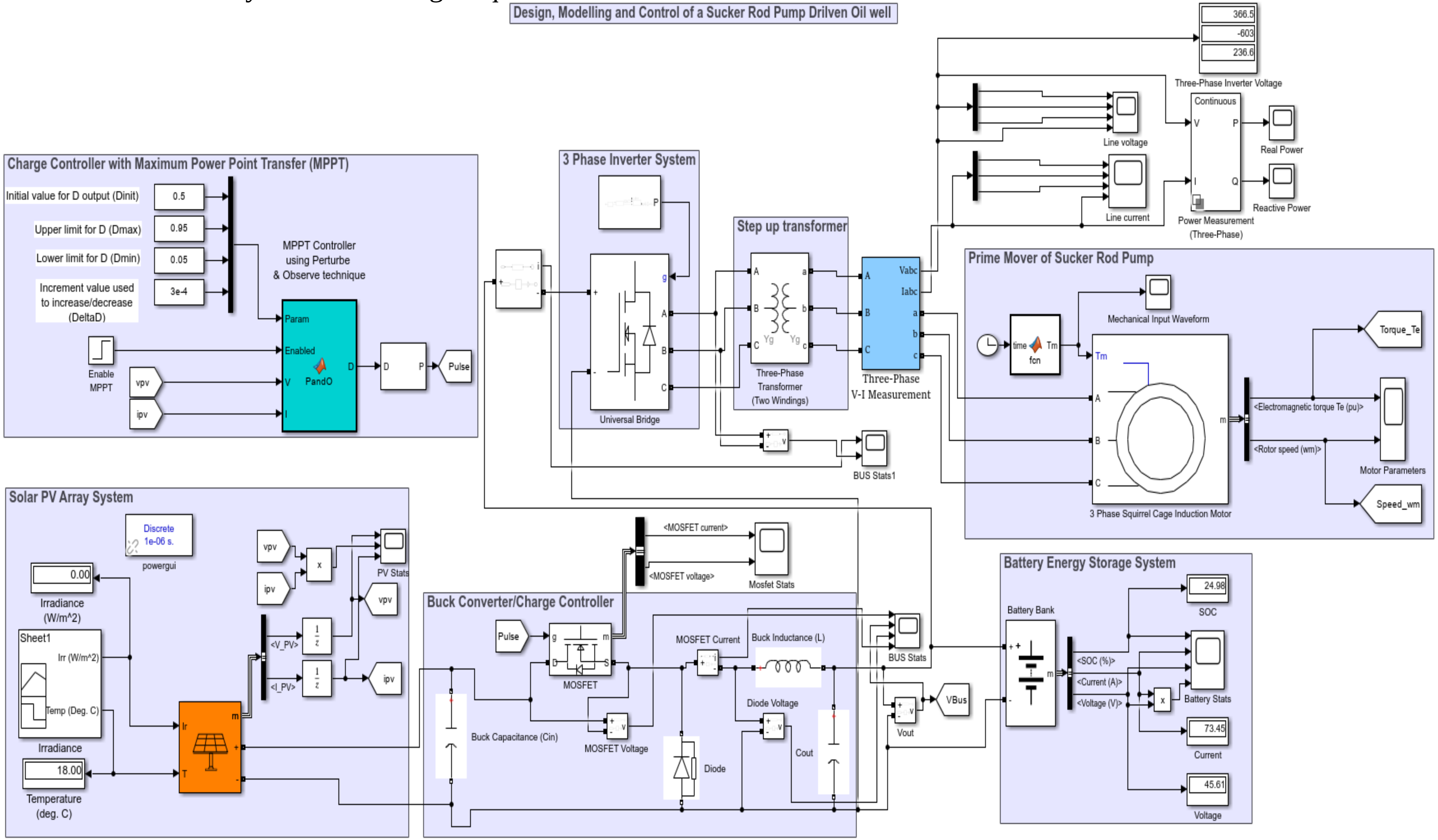

Fig 70 System Configuration : Circuit diagram showing subsystems modeled to achieve 100% microgrid

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Conclusion and Summary of Results

- Provides a complete picture of the system's behavior, allowing for the identification of opportunities for efficiency optimization at each subsystem.
- Decouples the microgrid into subsystems, supporting efficiency enhancements and performance improvement across the entire system from power source to load.
- Supports adaptation to various environmental and operating conditions, so potential issues can be identified and addressed before prototyping and real-world implementation.
- Incorporates load modeling from SolidWorks and Simscape into the Simulink model, providing a more realistic representation of the actual system, and leading to more reliable simulation results.
- The interdisciplinary approach combines mechanical (SolidWorks) and electrical (Simscape) models which is crucial for designing effective control algorithms for the sucker rod pump.

Final Conclusion of Research Work : Summary

In Chapter 2

- An integrated approach is adopted for optimal sizing of the sucker rod pump artificial lift system combining two (2) artificial lift simulators that are integrated for automated sizing.
- A sucker-rod artificial lift system is optimally sized for a case study oil well, to obtain the minimum API rating of the pumping unit, sustain the target production rate, and determine the corresponding minimum prime mover required to drive the pump sustainably.

In Chapter 3

- Feasibility study is successfully completed for the remote oil well, various pumping modes are identified and combined with different renewable energy configurations to identify the optimal scenario based on certain key performance indicators.
- The research recommends solar photovoltaic, wind turbine, and battery storage (with the least unmet load) for continuous pumping scenario, and solar photovoltaic and battery storage (with the least system cost) but with slightly higher unmet load for intermittent pumping.

In Chapter 4

- The Internet of things data transmission and communication system of the sucker rod pump was implemented using a low-cost open-source approach.
- Various sensors are deployed to measure key sucker rod pump parameters and relay to the local terminal units.
- Terminal units are used for transmitting and aggregating sensor data to the master terminal unit on the local server.
- Data monitoring, logging and transmission was implemented for remote control of the electric motors and sensors deployed to track the sucker rod pump performance which drives the low-flow rate oil well.

In Chapter 5

- Design, dynamic modeling, simulation, and control of a sucker rod-powered oil well was completed in Matlab/simulink
- The Sucker rod pump was first modelled in Solidworks and then transferred to simscape where the microgrid design was integrated with the sucker rod pump load model.
- The dynamic modelling and simulation is integrated with historical average daily solar irradiance and temperature data to demonstrate that the 100% solar energy microgrid design was capable of sustainably driving the sucker rod pump for reliable operation.

Conclusion : Research Contributions

Based on the research objectives provided, the research has the following 5 key research outcomes/contributions:

Sucker Rod Pump Design Simulator Integration: Development of an integrated methodology for optimal sizing of beam-pumped artificial lift systems for remote oil wells, combining parametric investigations and petroleum production system simulations.

Feasibility Study of Intermittent versus Continuous Production: Optimization of the design and sizing of hybrid renewable energy systems (solar, wind, battery storage) to power a remote oil well, evaluating the technical performance of intermittent vs continuous production.

Feasibility Study of 100% (Solar + Battery) Versus 100% (Solar + Wind + Battery): Evaluation of the feasibility and benefits of adopting renewable energy-based approaches for continuous and intermittent oil production, considering factors like unmet load, storage capacity, net present cost, and levelized cost of energy, evaluating economic performance of intermittent vs continuous production.

Open-Source technology: Design and implementation of a cost-effective, open-source IoT-based SCADA system for remote monitoring and control of a low-flowrate oil well, using serial communication in Arduino Uno and firmata in Arduino Mega microcontrollers as terminal units, enabling real-time data visualization, secure remote access, and integration of multiple sensors and transducers.

Load and System Modelling: Design, Dynamic Modelling, Simulation and Control of a 100% renewable energy-powered microgrid for remote oil wells, assessing its stability and performance under various environmental and operating conditions.

Conclusion

Future Work

- Expanding the scope of the integrated sizing approach for sucker rod pumps to beyond beam pumps to other artificial lift methods, to include a wider range of well conditions and production scenarios.
- Incorporating feature engineering and advanced machine learning algorithms to optimize the parameter selection process and further reduce iteration time.
- Adopting machine learning to reduce the iteration time and accuracy required for optimal sizing of sucker rod pump-powered oil wells.
- Comparing the energy efficiency and economic benefits of this approach across different oil fields, geological formations and geographical contexts.
- Investigating the technical and economic feasibility of a 100 % wind-powered oil well, comparing the use of hydraulic versus electric power from wind turbines to drive oil wells.
- Investigating the design, modelling, simulation and control of a 100% solar and wind energy powered oil well with various artificial lift configurations
- Exploring the technical and economic feasibility of grid-tied solar and wind energy systems in oil well oil, accounting for the carbon footprint of renewable energy integration and estimating the scope 1 and scope 2 emissions abated in MtCO2e.
- Integrating advanced energy storage technologies, such as flow batteries or hydrogen fuel cells, into the microgrid and investigating to improve system reliability and reduce costs.
- Conducting field trials in diverse geographical locations and well conditions.
- Transitioning the Node-RED application to a cloud-native platform, to enhance robustness, reliability and cyber-physical resilience.
- Implementing email alerts and notifications to enhance real-time monitoring capabilities.
- Mounting the transducers and sensors on a 3D model of a sucker-rod pump and integrating artificial intelligence and machine learning algorithms to develop a calibrated digital twin.
- Adoption of machine learning-powered algorithms for maximum power point tracking to effectively track maximum power from the solar PV arrays, using historical and real-time measured data.
- Investigating the dynamic modeling, simulation and control of other renewable energy sources, such as wind or geothermal, to create a more robust and diversified power supply for the oil well.
- Development of advanced control systems to drive the performance of the induction motor prime mover.
- Design and deployment of special motors and more sophisticated energy storage systems, possibly exploring emerging technologies like flywheels, flow batteries or hydrogen for energy savings in sucker rod pump driven oil wells.
- Scaling up the model to simultaneously simulate and optimize multiple interconnected induction motors prime movers powering several oil wells as in a typical conventional an oilfield system.

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