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Real-time Analysis of Inverter Performance via SCADA Haiwell Online Monitoring

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ABSTRACT

An inverter is the main component of an on-grid solar system. It converts DC power from solar PV to AC power to serve the electric load. Besides, it is used to find the maximum power point tracking and regulate the electric power from the main power and backup. This research discusses the development of an online inverter 40 kW monitoring system on the 38 kWp rooftop solar system at Pamulang University. The existing inverter monitoring system is by iSolarCloud application. This monitoring system can be accessed from the local area by scanning a QR code and Bluetooth connection. This system provides several output parameter information of the inverter, such as voltage, current, and power generation. The SCADA Haiwell has been used to construct the monitoring system. This system consists of the Programmable Logic Controller (PLC) Haiwell AC10S0R, Human Machine Interface (HMI) C7S-W, and Haiwell cloud application. The PLC reads the data from the input and output inverter by Modbus TCP/IP communication. The result of the monitoring system provides more parameters on both sides of the inverter input and output data. The Input side parameters include DC voltage, current, and DC power. The Output side parameters include AC voltage, current, grid frequency, active power, reactive power, daily yield power, total yield power, and efficiency of the inverter. The system's accuracy has been validated by comparing the HMI data, SCADA Haiwell Cloud and iSolarCloud readings. From the testing, this monitoring system is valid for monitoring the inverter performance online (mobile phones or PC).

1. Introduction

An essential component in the Solar Photovoltaic (SPV) system is an inverter [1]. The performance of the inverter greatly affects the SPV system efficiency. Since the SPV system has an issue with its efficiency, the inverter enhances it with maximum power point tracking (MPPT) system [2]. There exist many types of topologies of inverters to find the optimum power based on using it to convert the DC power from solar PV to AC power to serve the load [3,4]. In the on-grid system, the

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electric load serves in two ways that's power grid and the power output of an inverter as in Figure 1 [5]. Based on Figure 1, the data of the on-grid system is monitored via the inverter. It is because the inverter provides the information from the solar panel and the loads.

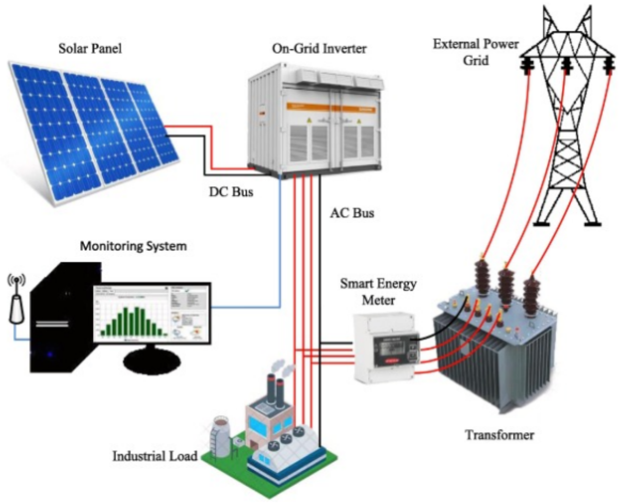


Fig. 1. The schematic of the on-grid PV system [6]

The real-time status of an SPV system can be monitored using several methods as reported in the literature, such as; Power Line Communication [7], GSM wireless [8], and the Internet of Things (IoT) [9]. Through such reporting, the performance of the SPV system can be evaluated. Typically, the SPV monitoring system represented by block diagrams consists of sensors, signal processing, signal conditioning, data transmission, data storage, and data analysis [10]. The real-time data is measured by the sensor, in which the signal processing is conducted further. The output data from signal processing is further processed in microcontroller-based signal conditioning and sent to data storage. These methods provide a real-time monitoring solution, in which processing the information without interruption. Through this practice, we can therefore indicate that the PV setup is in optimized condition [11].

Several works in the literature have documented various implementations of hardware [12-14] and software [15-17] in constructing the SPV monitoring system [18-20], especially concerning the real-time inverter monitoring system [21-25]. The trend in the recent five years is mostly revolving around the concept of IoT. Such concepts consist of interconnected sensors, monitoring systems, automated processing, and actions via the internet. In the context of SPV, an IoT system was implemented in the works of [26] to monitor the voltage and current of the inverter using wifi and Bluetooth module [27,28]. Although wifi and Bluetooth is technically feasible, such system is limited by range. Therefore Wu *et al*., [29] and Kim *et al*., [30] introduced the use of Long Range (LoRA) and 4G to overcome range limitation.

Using wireless technology in the transmission of data collected from the PV system is a profitable and promising method [31]. The use of the internet of things to monitor solar panel performance such as output power and energy can improve energy management and efficiency [32]. The implementation of Supervisory Control and Data Acquisition (SCADA) in hybrid system monitoring provides superior features in terms of cost-effectiveness and system reliability [33]. From the literature above there isn't research related to using the programmable logic controller (PLC) as a monitoring system.

In this work, the implementation of Scada Haiwell to build an online inverter monitoring system is presented, in which the outcome of the system is analyzed in-depth. The measurement of the inverter parameters directly uses the PLC. The on-grid SPV system at Pamulang University was built on the rooftop with a capacity of 38 kWp. This on-grid SPV is connected to a 40 kW Sungrow Inverters. By default, the 40 kW inverter has a limited capability monitoring system which is on the access method and the data logger. In its initial setup, the performance parameters of the inverter can only be accessed from the local area via Bluetooth connection on a smartphone application. Therefore, inverter monitoring system has a limited range of connections in which the output data can only be obtained in the inverter room or a maximum of 21 meters. By default, the output parameter that the data logger provides is just the energy yield and the active power within 5 days with intervals of 12 minutes for every recording. Such limitations characterized the default configuration of this system hinders the means to obtain and analyze data in real-time. This motivates the implementation of online monitoring system of the Scada Haiwell as presented in this work.

2. Methodology

2.1 Step of the Research

The research has been done by following some stages sequentially, as on the flow chart in Figure 2.

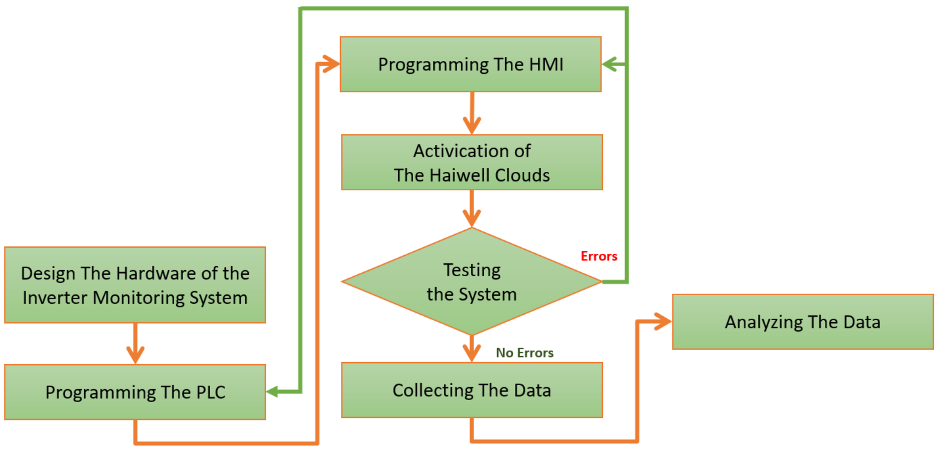


Fig. 2. The methodology flow chart

Table 1
The PV Modules Data Sheet

Parameters	Range
Nominal Max. Power (Pmax)	480 Watt
Opt. Operating Voltage (Vmp)	44 Volt
Opt. Operating Current (Imp)	10,91 Ampere
Open Circuit Voltage (Voc)	52,7 Volt
Short Circuit Current (Isc)	11,57 Ampere
Module Efficiency	20,4 %
Operating Temperature	+85° C
Cell Type	Mono-crystalline
Dimensions	2250x1048x35 mm

The main component, such as the PV module, the inverter, PLC, and HMI, have data sheets as shown in Table 1, Table 2, and Table 3. The module is using monocrystalline type. The capacity of the inverter is 44 kVA, and the HMI has Modbus/Ethernet IP communications.

Table 2
The Sungrow Grid-Connected PV Inverter Data Sheet

Parameters	Range
Max. Input Voltage	1100 Volt
Min. MPP Voltage	200 Volt
Max. MPP Voltage	1000 Volt
Max. Input Current	104 Ampere
Isc PV	106 Ampere
Nominal AC voltage	3 / N / PE, 230 / 400 V
AC voltage range	312 to 528 Volt
Nominal grid frequency / Grid frequency range	50/60 Hz
Max. AC output current	66,9 Ampere
Max. Apparent Power	44 kVA
AC output power	40 kW
Power Factor Range	0,8 Leading … 0,8 Lagging
Max. efficiency	98,6%
Dimensions	2250x1048x35 mm

Table 3
The PLC and HMI Data Sheet

Parameters	Range
PLC Model	AC10S0R
Digital Input	6
Digital Ouput	4
Analog Input	2 (0-10 VDC)
Memory Capasity	12 bits
PLC Communications	Modbus/Ethernet IP
PLC Software Programming	HaiwellHappy V2.2.10.
HMI Model	Haiwell HMI C7S
Communications	Modbus/Ethernet TCP/IP
HMI Software Programming	Haiwell Cloud Scada Desaigner

2.2 The on-grid SPV system Pamulang University

The on-grid SPV system consists of 96 PV modules that are connected to the Inverter. These modules are distributed in 3 string array with 16 modules in each string as shown in Figure 3. The PV module configuration aims to adjust the number of available MPPT on the inverter.The data sheet of the PV modules is in Table 1. The total capacity of the SPV system is defined by equation (1)[34].

$$P_{wattpeak} = \frac{P_{mpp}}{Amount\ of\ PV\ Modules} \quad (1)$$

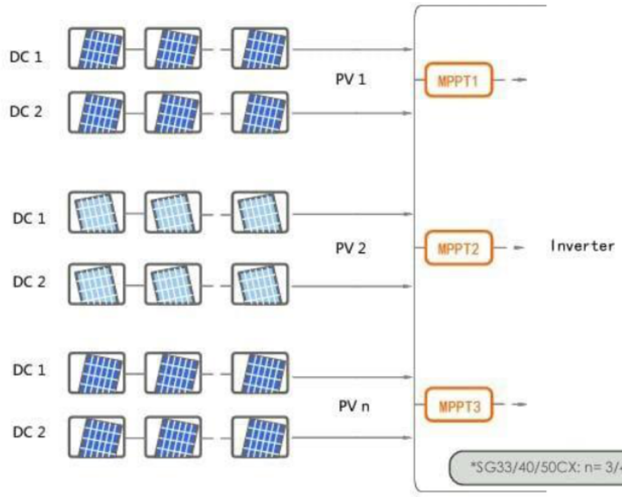


Fig. 3. The schematic of string array of PV modules to the Inverter

The on-grid SPV system of Pamulang University was installed on the rooftop of building B with the coordinates $6^0$20,8'LS, $106^0$41,5'BT Tangerang Selatan. The block diagram of the system is shown in Figure 4. Since the power generation of the SPV depends on solar radiation, the reliability of the system was back-up by grid power and a diesel generator. These power generations are synchronized at the panel meter after the inverter changes DC power from PV modules to AC power. The Inverter becomes an important component since it is duty to supply the load.

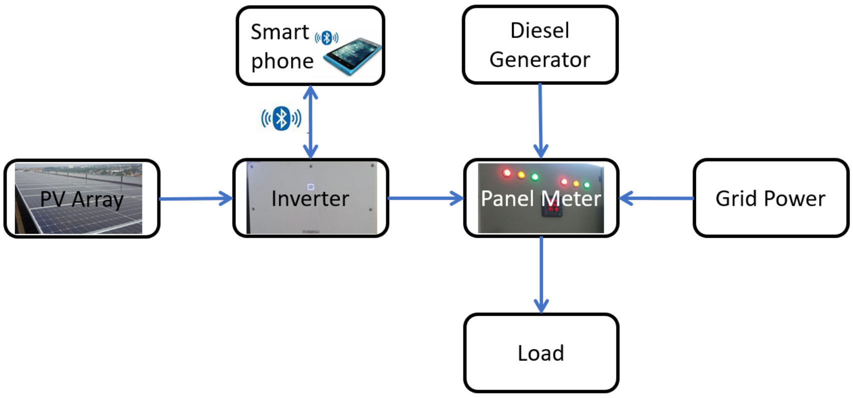


Fig. 4. The on-grid SPV system Pamulang University

Some parameters provided by the inverter are the input side and the output side. The input parameters consist of each MPPT DC Voltage (V_{mppt1}, V_{mppt2}, V_{mppt3}), DC Current (I_{mppt1}, I_{mppt2}, I_{mppt3}), and Total DC Power. The output parameters consist of Energy Yield (Daily Yield, Monthly Yield, Annual Yield, Total Yield), AC Power (Active Power, Reactive Power, Apparent Power), Power Factor, Grid Frequency, the phase AC voltage (V_R, V_S, V_T) and the phase AC Current (I_R, I_S, I_T). The inverter provides a two-parameter data logger which is the power curve and the energy yield. The power curve data is the data for five days later with 12 minutes interval data and the energy yield data are the daily, monthly, and yearly since the SPV begin in operation.

2.3 Development of the Inverter Monitoring system

PLC and HMI are the main components used to convert the inverter monitoring system from the Bluetooth method to the online method as shown in Figure 5 (in the red bracket). The communication between the inverter, PLC, and HMI uses Modbus TCP/IP protocol. Each component must have a different address while communicating via the Modbus protocol. The PLC and HMI can read the data from the inverter as long as the mapping address on the PLC ladder diagram syncs with the HMI design.

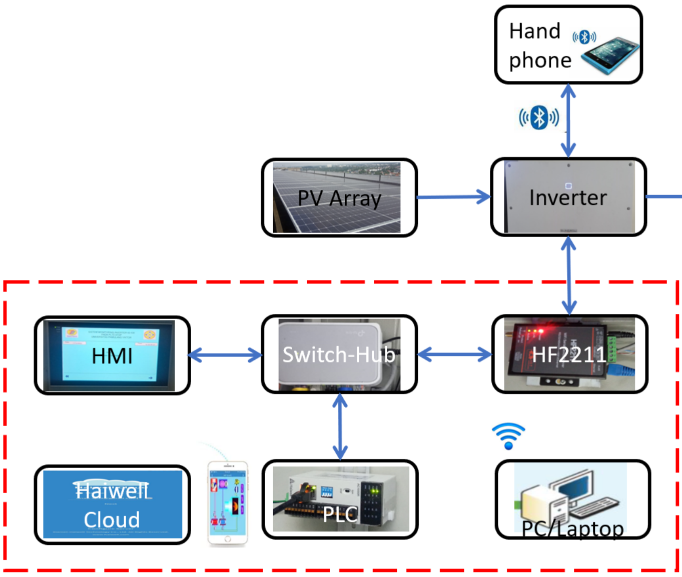


Fig. 4. The online inverter monitoring system.

The address of PLC and HMI to read the parameter from the Inverter is shown in Table 4.

Table 4
The Parameter and address for Ladder PLC and HMI Programming.

Parameter	PLC Address	HMI Address	Note
DC Power	5016	126	DC Power Input Inverter
Vmppt1	5010	128	DC Voltage Input Inverter MPPT1
Vmppt2	5012	132	DC Voltage Input Inverter MPPT2
Vmppt3	5014	136	DC Voltage Input Inverter MPPT3
Imppt1	5011	130	DC Current Input Inverter MPPT1
Imppt2	5013	134	DC Current Input Inverter MPPT2
Imppt3	5015	138	DC Current Input Inverter MPPT3
Daily Yield	5002	104	Energy for 1 day
Total Yield	5005	106	Energy total since the first production
V_R	5018	108	AC Voltage Output Inverter Phase R
V_S	5019	110	AC Voltage Output Inverter Phase S
V_T	5020	112	AC Voltage Output Inverter Phase T
I_R	5021	114	AC Current Output Inverter Phase R
I_S	5022	116	AC Current Output Inverter Phase S
I_T	5023	118	AC Current Output Inverter Phase T
S	5008	124	Total Apparent Power Output Inverter
P	5030	120	Total Active Power Output Inverter
Q	5032	122	Total Reactive Power Output Inverter
Cos φ	5034	102	The Grid Power Factor
F	5035	100	The Grid Frequency

2.4 Accuracy of the Monitoring System

The accuracy is the similarity between the measurement value and the actual value [35]. The accuracy of the monitoring system is defined by comparing the data between online and Bluetooth methods. The accuracy percentage of the system and the average can be defined by equation 2 and equation 3 [36].

$$\% \, Error = \frac{The\ Bluetooth\ \ Data - The\ Online\ Data}{The\ Bluetooth\ Data} \ x \ 100\ \% \tag{2}$$

$$Average\ Error = \frac{The\ Number\ of\ Errors}{Amount\ of\ the\ data} \ x \ 100\ \% \tag{3}$$

3. Results

3.1 The hardware of the monitoring system

The hardware and connection of the monitoring system can be shown in Figure 5. The monitoring system has a power supply and a mini circuit breaker. A power supply converts 220 Vac to 24 Vdc that use to supply the PLC and HMI. The mini circuit breaker has a capacity of 4A to protect the system from short circuit faults.

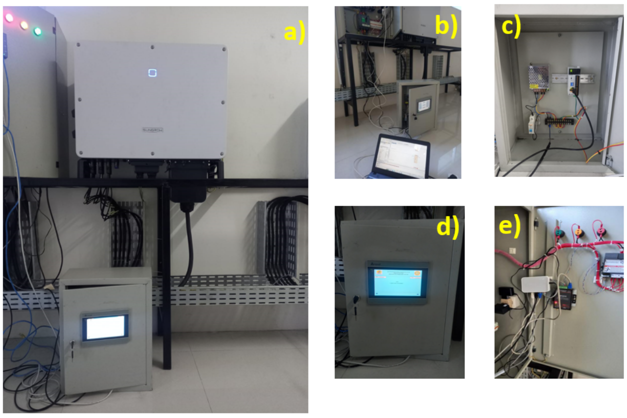


Fig. 5. The hardware of the monitoring system (a) *Overview the System (b) PLC, HMI, and Laptop Connection (c) Wiring Installation of the system in the panel (d) Display of the HMI (e) Connection of WiFi Serial Device Server and Desktop Switch*

3.2 The running program of the monitoring system

3.2.1 The Ladder Diagram of PLC

To test the ladder diagram of PLC by transferring the ladder diagram program from the laptop to PLC. When the program has already succeeded in PLC, select the online icon on the Haiwell Happy V2.2.10. and choose the TC/IP 10.22.0.230. The result of the ladder diagram running program for the input parameter as is shown on in Figure 6.

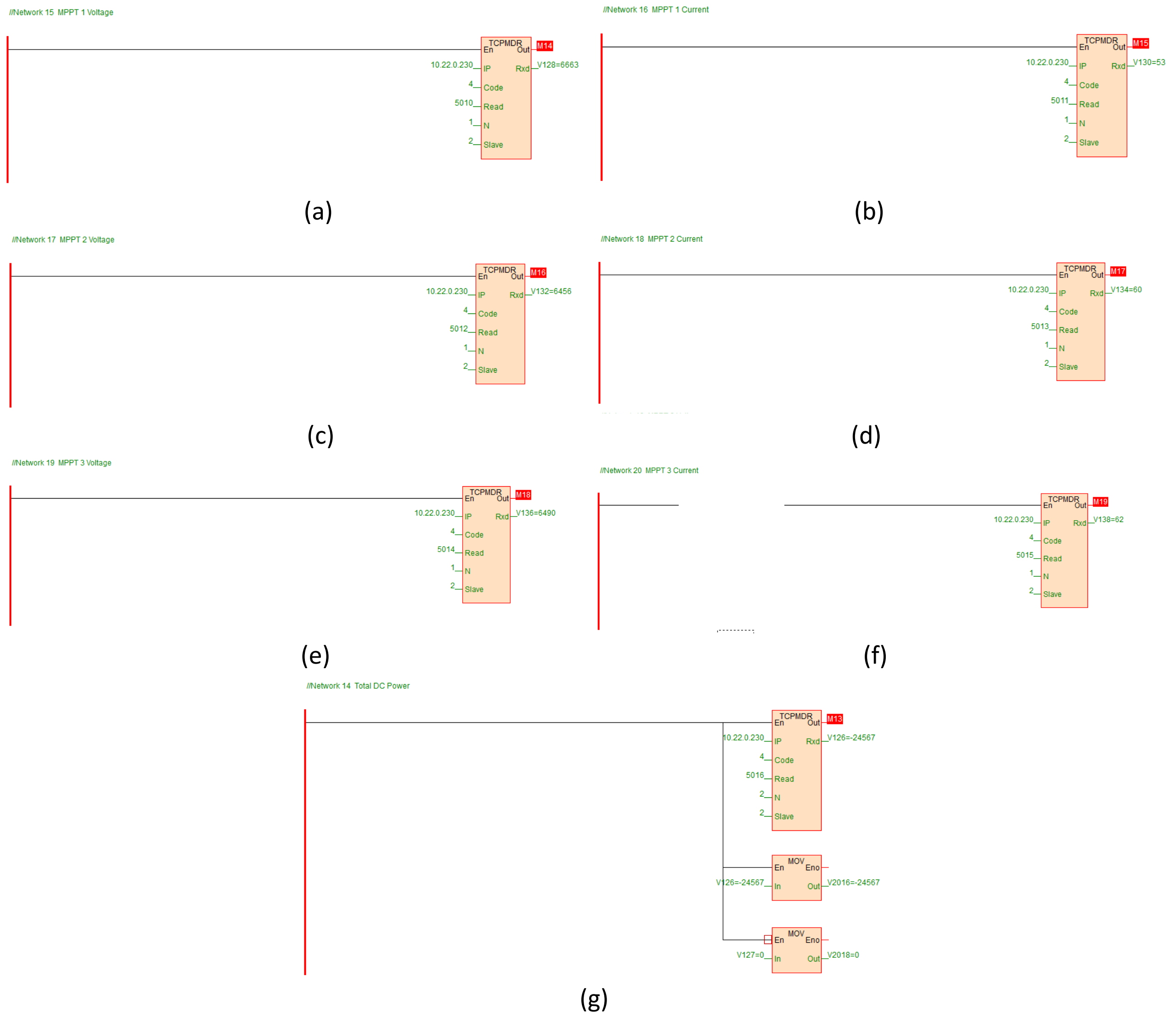
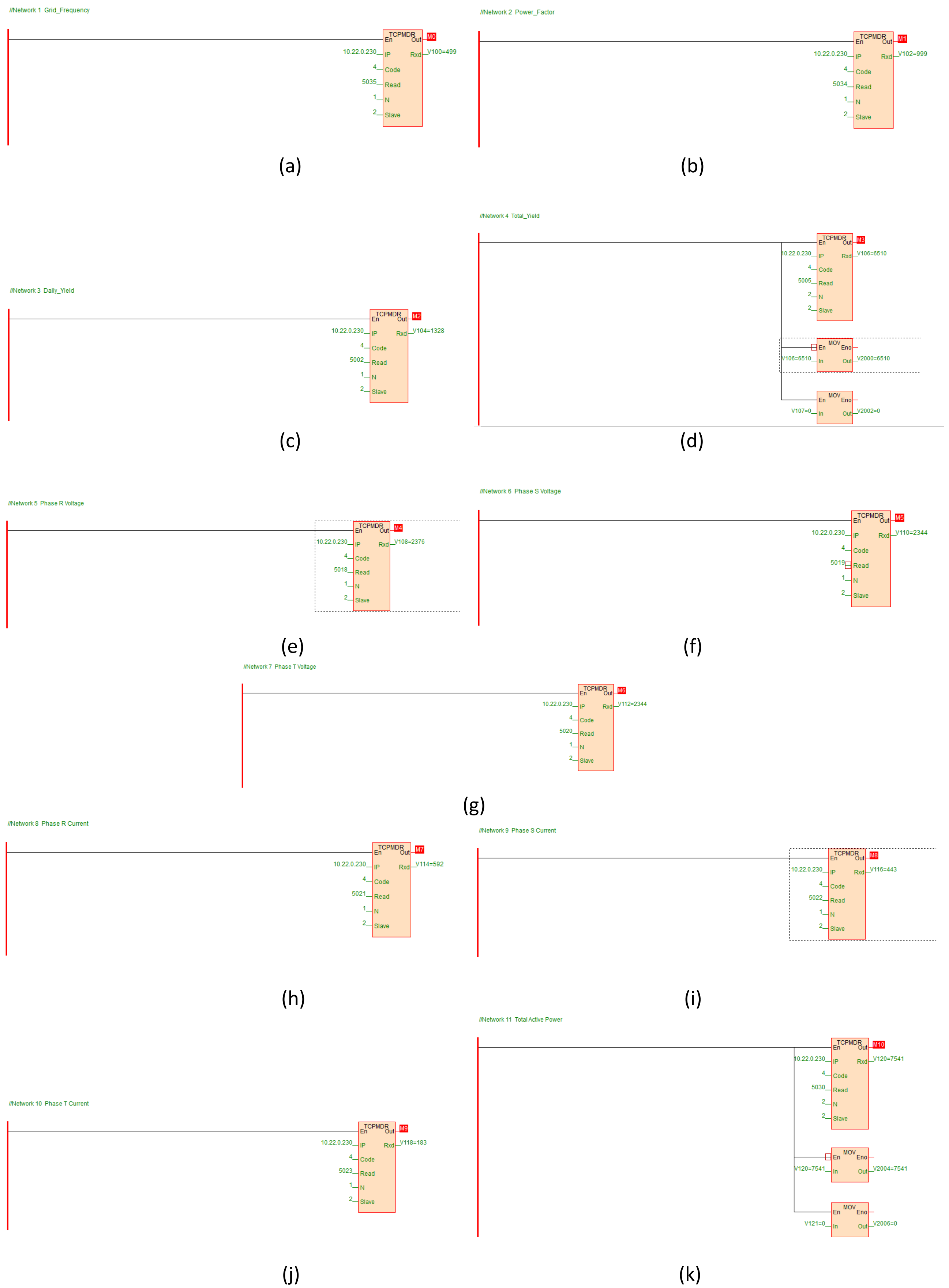
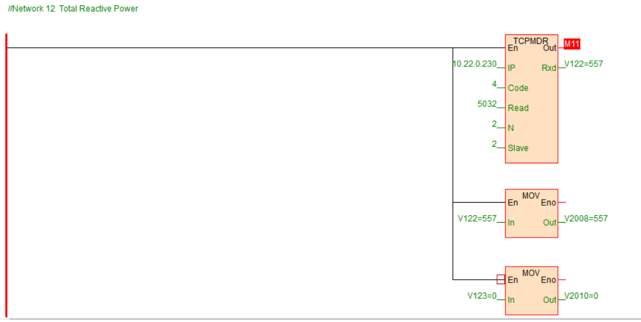


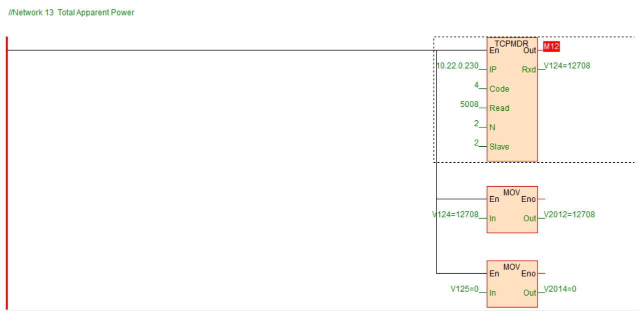
Fig. 6. The running ladder diagram for Input Inverter Parameter (a) MPPT 1 Voltage (b) MPPT 1 Current (c) MPPT 2 Voltage (d) MPPT 2 Current (e) MPPT 3 Voltage (f) MPPT 3 Current (g) Total DC Power

Figure 6 (a) – (g) shows the active address and measurement value for each input parameter. The read state is for the PLC address and the Rxd state is for the HMI address as set in Table 4. The measurement value for each parameter is MPPT 1 Voltage = 666.1 V, MPPT 1 Current = 5.3 A, MPPT 2 Voltage = 645.6 V, MPPT 2 Current = 5 A, MPPT 3 Voltage = 649 V, MPPT 3 Current = 6.2 A, and Total DC Power = 24,57 kW.

Figure 7 shows the result of the ladder diagram running program for the the output Inverter parameter.


//Network 1 Grid_Frequency
TCPMDR
M0
10.22.0.230
V100=499
(a)
//Network 2 Power_Factor
TCPMDR
M1
10.22.0.230
V102=999
(b)
//Network 3 Daily_Yield
TCPMDR
M2
10.22.0.230
V104=1328
(c)
//Network 4 Total_Yield
TCPMDR
M3
10.22.0.230
V106=6510
MOV
V2000=6510
V107=0
V2002=0
(d)
//Network 5 Phase R Voltage
TCPMDR
M4
10.22.0.230
V108=2376
(e)
//Network 6 Phase S Voltage
TCPMDR
M5
10.22.0.230
V110=2344
(f)
//Network 7 Phase T Voltage
TCPMDR
M6
10.22.0.230
V112=2344
(g)
//Network 8 Phase R Current
TCPMDR
M7
10.22.0.230
V114=592
(h)
//Network 9 Phase S Current
TCPMDR
M8
10.22.0.230
V116=443
(i)
//Network 10 Phase T Current
TCPMDR
M9
10.22.0.230
V118=183
(j)
//Network 11 Total Active Power
TCPMDR
M10
10.22.0.230
V120=7541
MOV
V2004=7541
V121=0
V2006=0
(k)





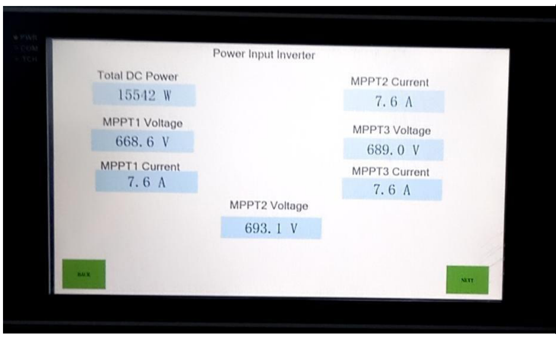
(l) (m)

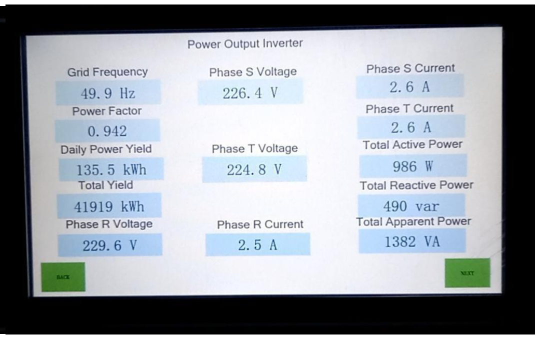
Fig. 7. The running ladder diagram for Input Inverter Parameter (a) Grid Frequency (b) Power Factor (c) Daily Yield (d) Total Yield (e) R Phase Voltage (f) S Phase Voltage (g) T Phase Voltage (h) R Phase Current (i) S Phase Current (j) T Phase Current (k) Total Active Power (l) Total Reactive Power (m) Total Apparent Power

Figure 7 (a) – (m) shows the active address and measurement value for each output parameter. The read state is for the PLC address and the Rxd state is for the HMI address as set in Table 4. The measurement value for each parameter is Grid Frequency = 49.9 Hz, Power Factor = 0.99, Daily Yield = 132.8 kWh, Total Yield = 6 510 kWh, R Phase Voltage = 237.6 V, S Phase Voltage = 234.4 V, T Phase Voltage = 183 V, R Phase Current = 59.2 A, S Phase Current = 44.3 A, T Phase Current = 18.3 A, Total Active Power = 7 541 W, Total Reactive Power = 557 VAR, and Total Apparent Power = 12 708 VA.

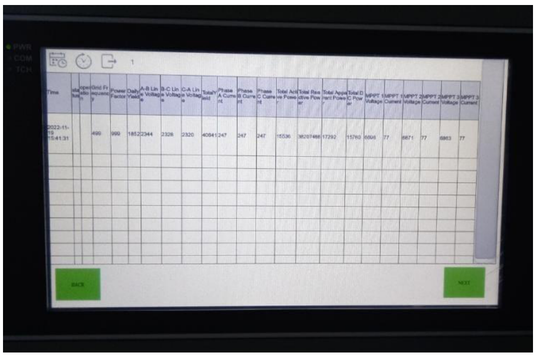
3.2.2 The running Program of HMI

Figure 8 shows the display of the HMI. There are three-page on the HMI display due to the input parameter page, the output parameter page and the data logging page. By touchscreen method, the each page on the HMI can see by touch previous and next button.





(a) (b)

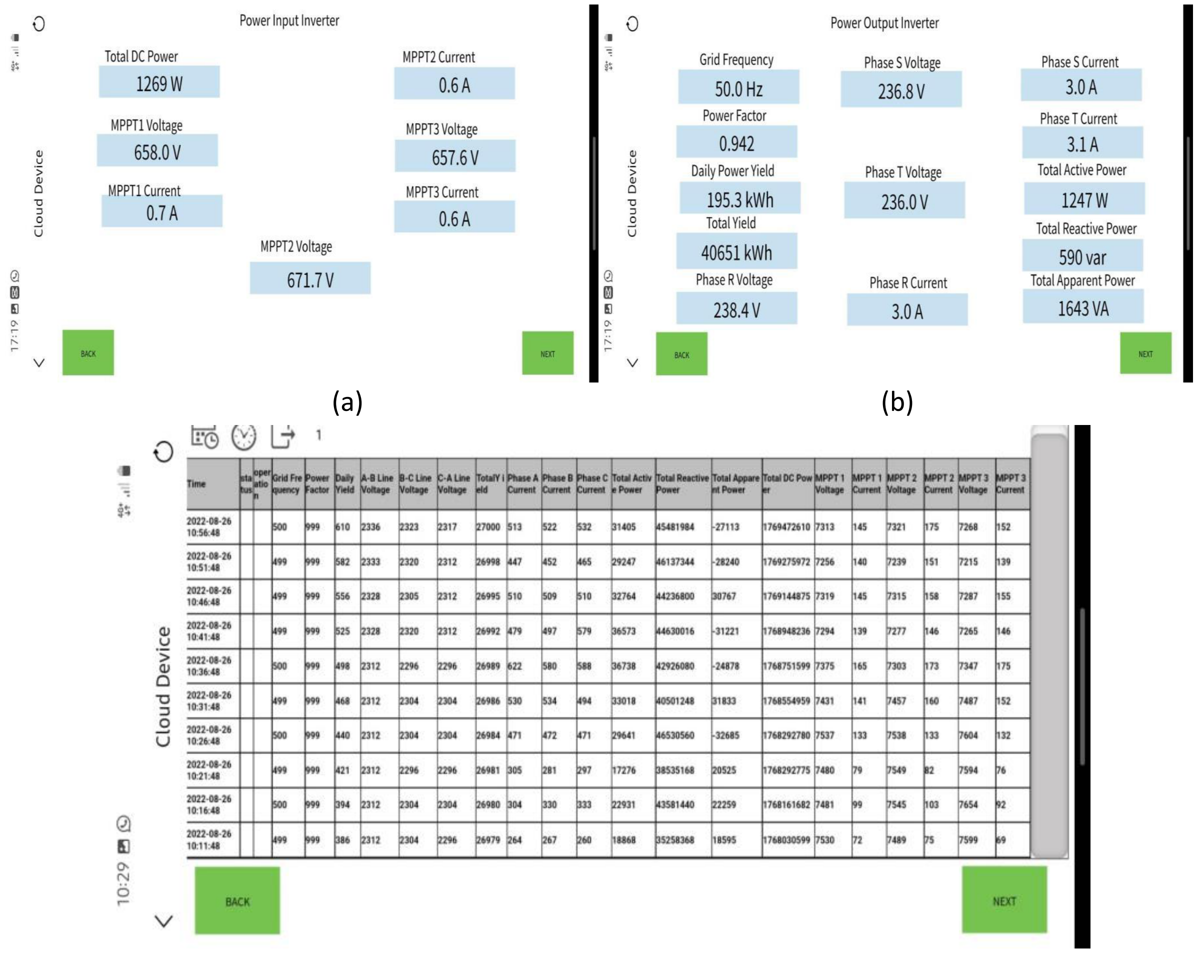


(c)

Fig. 8. The Display of HMI (a) Input Inverter (b) Output Inverter (c) Data logger

3.2.3. The Haiwell Cloud

Haiwell Cloud is a useful application for monitoring inverter parameters via smartphone. Through Haiwell Cloud all inverter parameters can be monitored online. With this online method, inverters can be monitored anywhere which has an impact on time efficiency compared to having to go to the inverter room. The display on the handphone is in accordance with the page contained in the HMI.



Time	status	operation	Grid Frequency	Power Factor	Daily Yield	A-B Line Voltage	B-C Line Voltage	C-A Line Voltage	TotalYield	Phase A Current	Phase B Current	Phase C Current	Total Active Power	Total Reactive Power	Total Apparent Power	Total DC Power	MPPT 1 Voltage	MPPT 1 Current	MPPT 2 Voltage	MPPT 2 Current	MPPT 3 Voltage	MPPT 3 Current
2022-08-26 10:56:48			500	999	610	2336	2323	2317	27000	513	522	532	31405	45481984	-27113	1769472610	7313	145	7321	175	7268	152
2022-08-26 10:51:48			499	999	582	2333	2320	2312	26998	447	452	465	29247	46137344	-28240	1769275972	7256	140	7239	151	7215	139
2022-08-26 10:46:48			499	999	556	2328	2305	2312	26995	510	509	510	32764	44236800	30767	1769144875	7319	145	7315	158	7287	155
2022-08-26 10:41:48			499	999	525	2328	2320	2312	26992	479	497	579	36573	44630016	-31221	1768948236	7294	139	7277	146	7265	146
2022-08-26 10:36:48			500	999	498	2312	2296	2296	26989	622	580	588	36738	42926080	-24878	1768751599	7375	165	7303	173	7347	175
2022-08-26 10:31:48			499	999	468	2312	2304	2304	26986	530	534	494	33018	40501248	31833	1768554959	7431	141	7457	160	7487	152
2022-08-26 10:26:48			500	999	440	2312	2304	2304	26984	471	472	471	29641	46530560	-32685	1768292780	7537	133	7538	133	7604	132
2022-08-26 10:21:48			499	999	421	2312	2296	2296	26981	305	281	297	17276	38535168	20525	1768292775	7480	79	7549	82	7594	76
2022-08-26 10:16:48			500	999	394	2312	2304	2304	26980	304	330	333	22931	43581440	22259	1768161682	7481	99	7545	103	7654	92
2022-08-26 10:11:48			499	999	386	2312	2304	2296	26979	264	267	260	18868	35258368	18595	1768030599	7530	72	7489	75	7599	69

Fig. 9. Display Of Inverter Parameter on Haiwell Cloud with a typical data (a) Inverter Input Parameter (b) Inverter Output Parameter (c) Data Logger.

3.3 The Accuracy of the monitoring system.

3.3.1 The Measurement of the Inverter Input Parameters.

The inverter input parameters are the electric generation from SPV as wiring in Figure 3. The result of Haiwell Cloud and IsolarCloud measurements was used to find the online monitoring system's accuracy. Based on equation 2 and equation 3, the accuracy and its average are shown in Figure 10. The data was collages from one hour with the interval for each data along five minutes.

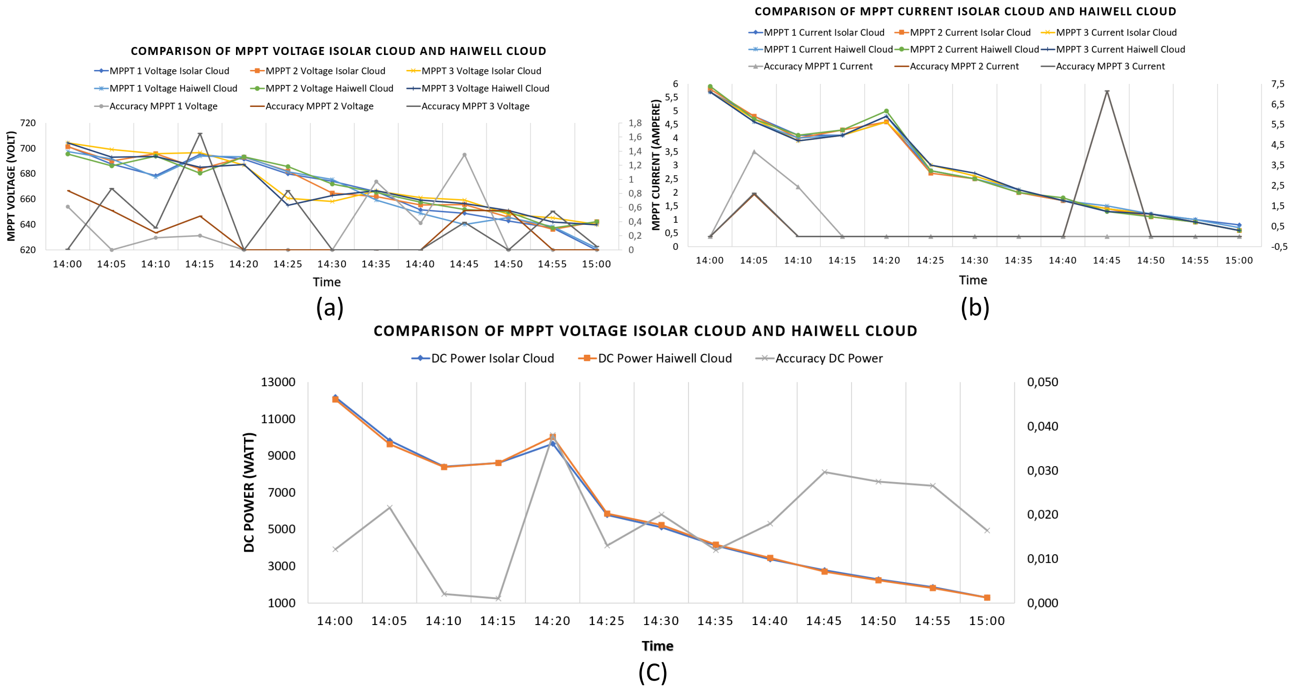
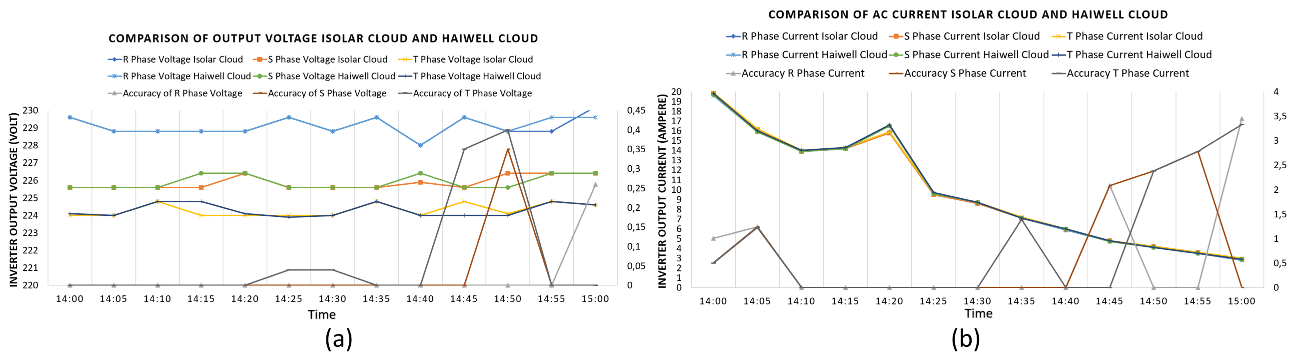


Fig. 10. The Accuracy of the Inverter Input Parameters (a) MMPT Voltage Accuracy (b) MPPT Current Accuracy (C) DC Power Accuracy

Based on Figure 10 (a) the high error of the MPPT Voltage measurement occurs in MPPT 3 with a percentage of 1.6 percent. The average error of all MPPT measurements is 0.28%. The maximum error for MPPT current at 7.14 percent with the average error for all measurements being 0.64%. The DC Power maximum error is 0.04% with an average error of 0.02%.

3.3.1 The Measurement of the Inverter Output Parameters.

The inverter output parameters are connected to serve the load. These parameters important to monitor to evaluate the inverter performance. Figure 11 (a) until (h) shows these measurements and the accuracy for each parameter.



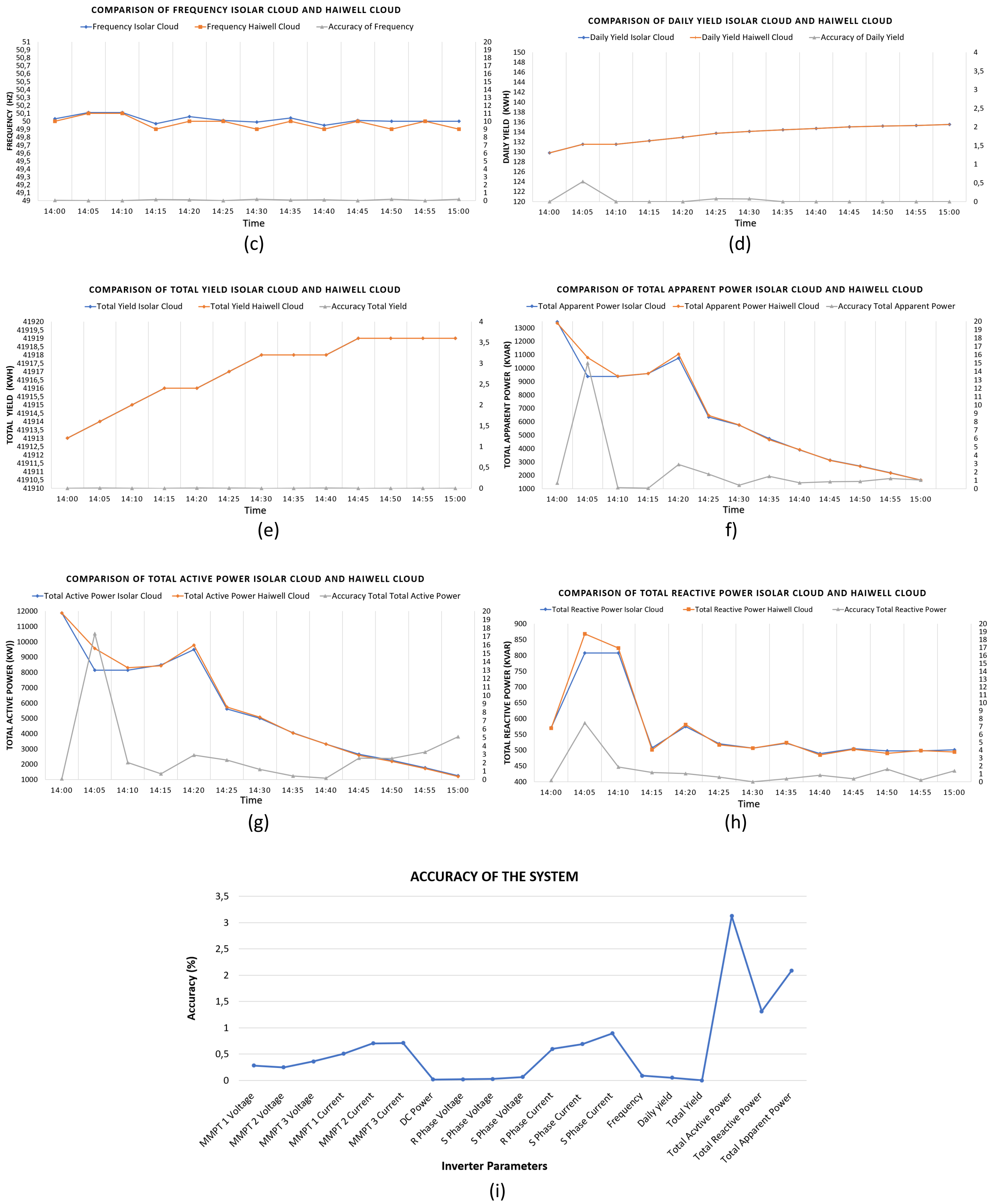


Fig. 11. The Accuracy of the Inverter Output Parameter (a) Voltage AC Accuracy (b) Current AC Accuracy (c) Frequency Accuracy (d) Daily Yield Accuracy (e) Total Yield Accuracy (f) Total Apparent Power Accuracy (g) Total Active Power Accuracy (h) Total Reactive Power Accuracy (i) The Accurate of the online monitoring system

Based on Figure 11 (a) the high error for Vac measurement occurs in 0.35 % with the average for all measurements being 0.037%. In Figure 11 (b) a maximum error occurs in the R phase current amount of 3.45%. The average error for this measurement is 0.73%. The accuracy for frequency, daily yield, and total yield are 0.091%, 0.056%, and 0.001% respectively. Figure 11 (f) until (h) shows the errors of electric power that is totally apparent power, total active power, and total reactive power. The average error for each electric power is sequenctly 2.20%, 3.36%, and 1.40%. Figure 11 (i) shows the graphic of average error for all measurement, input, and output parameters. From this graphic, the accuracy of the online monitoring system is 0.62%. Table 5 shows the analysis of inverter parameters in the statistic method.

Table 5
The Statistic Result of Inverter Parameter.

No	Parameter	Minimum	Median	Maximum	Mean	Average Errors	Standar Deviation
1.	MMPT 1 Voltage Isolar Cloud	619,7	674,2	701,7	667,3	0,28	24,26
2.	MMPT 1 Voltage Haiwell Cloud	621,3	675,4	697,4	666,4		24,52
3.	MMPT 2 Voltage Isolar Cloud	636,1	664,7	701,4	669,8	0,25	21,37
4.	MMPT 2 Voltage Haiwell Cloud	637,3	671,8	695,5	670,1		24,52
5.	MMPT 3 Voltage Isolar Cloud	639,9	661,2	704,4	670,9	0,36	21,68
6.	MMPT 3 Voltage Haiwell Cloud	639,6	662,8	704,3	668,9		20,45
7.	MMPT 1 Current Isolar Cloud	0,8	2,5	5,7	2,823	0,51	1,59
8.	MMPT 1 Current Haiwell Cloud	0,7	2,5	5,7	2,823		1,58
9.	MMPT 2 Current Isolar Cloud	0,6	2,5	5,8	2,8	0,71	1,65
10.	MMPT 2 Current Haiwell Cloud	0,6	2,5	5,9	2,846		1,69
11.	MMPT 3 Current Isolar Cloud	0,6	2,6	5,7	2,808	0,71	1,59
12.	MMPT 3 Current Haiwell Cloud	0,6	2,7	5,7	2,815		1,61
13.	DC Power Isolar Cloud	1298	5119	12200	5792	0,02	3432,84
14.	DC Power Haiwell Cloud	1277	5226	12053	5799		3437,32
15.	R Phase Voltage Isolar Cloud	228	229	230	229	0,02	0,56
16.	R Phase Voltage Haiwell Cloud	228	228,8	229,6	229,1		0,50
17.	S Phase Voltage Isolar Cloud	225,6	225,6	226,4	226	0,03	0,36
18.	S Phase Voltage Haiwell Cloud	225,6	225,6	226,4	225,9		0,39
19.	T Phase Voltage Isolar Cloud	224	224	224,8	224,3	0,06	0,37
20.	T Phase Voltage Haiwell Cloud	223,9	224,1	224,8	224,3		0,37
21.	R Phase Current Isolar Cloud	2,9	8,6	19,8	9,715	0,60	5,42
22.	R Phase Current Haiwell Cloud	2,8	8,7	19,6	9,731		5,44
23.	S Phase Current Isolar Cloud	2,9	8,6	19,8	9,723	0,69	5,39
24.	S Phase Current Haiwell Cloud	2,9	8,7	19,7	9,754		5,44
25.	T Phase Current Isolar Cloud	3	8,7	19,9	9,8	0,89	5,42
26.	T Phase Current Haiwell Cloud	2,9	8,7	19,8	9,808		5,48

4. Conclusions

The experimental result shows that the online monitoring system based on Scada Haiwell can improve the inverter monitoring system from the Bluetooth method to online access. Besides that, the new monitoring system provides the data logger containing all inverter parameters since the first operation. With an average error result is 0.621% make this system can be used to monitor the inverter performance and replace the old monitoring system.

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