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The Implementation of Storage Type Power Flow Controller using Battery Storage

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ABSTRACT

This paper describes the implementation of a Storage Power Flow Controller (SPFC) connected to the grid which can provide concomitant benefits associated with a Unified Power Flow Controller while at the same time providing several other very important benefits to power system operation such as, load leveling dynamic voltage stability improvement, harmonic compensation and power factor correction. This Storage Power Flow Controller (SPFC) was implemented using real time signal processors, three-phase inverter(s) and battery bank which can provide improved power system operation and control, added system security and reduced power system losses.

Key Words : Storage Power Flow Controller, Battery Energy Storage System, Unified Power Flow Controller, Flexible AC Transmission System.

1. Introduction

Before the concept of FACTS was introduced, power electronic controlled devices, such as static VAR compensators [1] have been used in transmission networks for many years. In 1988, the concept of FACTS as a total network control philosophy was introduced in the paper [2]. The flexible transmission system is akin to high-voltage dc transmission, designed to overcome the limitations of the mechanically controlled tap-changers, phase-shifters, and switched capacitors, and reactors in the ac power transmission systems [3]. FACTS technology [4-7] is not a single high power controller but rather a collection of controllers which can be applied individually or collectively to control the inter-related parameters such as voltage, phase angle, impedance, current, reactive power and active power. However, there is no active power storage capability in the devices and each device can provide control of few parameters only. Therefore, in a power transmission networks, many devices are required to provide entire control of the networks.

Battery Energy Storage (BES) is one of the options that can provide active power storage as well as delivering power when the ac system is needed. BES, for sure, comprises of battery bank and power conversion system, using nowadays high-speed reliable power electronics controllers, the technology offers utilities opportunities for increasing efficiency:

- Control power so that the desired amount flows on the desired routes.
- Greater ability to transfer power between controlled areas so that the generation reserve margin, typically 18 percent, can be reduced to 15 percent or less.
- Prevention of cascading outages by limiting the effects of faults and equipment failure.

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- Damping of power system oscillations which could damage equipment and/or limit usable transmission capacity.

This paper will describe a new proposal to utilize the state-of-the-art fast-switching power electronics, microprocessor control and energy storage for effective and fast control power flow along a transmission or distribution corridor, in many ways acting like a UPFC device, while at the same time providing additional benefits such as load leveling, damping of inter-area oscillations, damping transient stability and also provide active power filtering to meet power quality standards. This new device is being called the Storage PFC (SPFC), but unlike UPFC, the SPFC is most suited for application in the distribution system. This is one of the several topologies currently being explored to implement the above objectives using a Battery Energy Storage System (BESS) connected to the grid. The proposed multi-purpose SPFC can provide high-speed control of active and reactive power along a transmission corridor independent of its waveform. This paper will also demonstrate that the proposed SPFC actually provides all the UPFC control functions, such as voltage drop compensation, phase angle control and reactive power compensation. Results from experiments will be provided and discussed.

2. Implementations of Battery Energy Storage System (BESS)

The hardware of BESS consists of:

A) Real time accurate measurements of electrical quantities built around a Texas Instrument TMS320C31 3rd generation floating-point Digital Signal Processor (DSP). The board combines the TMS320C31's computing performance of up to 60 MHz, with a versatile set of on-board Input/Output (I/O). The DSP board has four (A/D) converters to sample the instantaneous values of two line voltages and two line currents during each sampling period. Using software based algorithm, these measured values are stored for further evaluations for control purposes.

B) A three-phase Inverter rated at 415V, 50A three phase output. It employed Insulated Gate Bipolar Transistor (IGBT) modules as the switching devices with switching speed of more than 15kHz, each rated at 600V and 60A with dead-time control of 1.5μsec. The module has been specially designed to protect the system from both internal and external fault and can in extreme circumstances run at twice at rated rating.

C) The lead-acid battery bank chosen for the project is low maintenance air-vented type consisting of 38, 6V modules connected in series to provide 220V dc, 100Ah capability. Each battery module, has three cells connected in series, can last for 10 hours at 10-ampere with end voltage equal to 1.8V per cell.

2.1 Control implementation using DSP

The BESS control implementation is shown in Fig. 1. Fig. 1 shows that the DSP-Board sampled two voltages and two currents from the analog-to-digital converters (ADC's) and then output three PWM signals from the input/output (I/O) pins to the dead-time controller. Finally, six PWM signals are sent to the power conversion system for control. While processing the input and output signal, the DSP-Board executes the programmed control process. The written software is first compiled into a machine code and then loaded into the memory for execution. The software consists of instructions that direct the DSP-Board to carry out the designed tasks such as to initialize the DSP-board, to activate the ADCs and I/O pins, to take control action while fetching the control variables (i.e. voltage and current), to monitor and provide a facility to alter the control references at any time even while the DSP is running.

The control strategy comprises of a hysteresis band controller and a phase shift controller. Fig. 2 shows the structure of the controller in a three-phase BESS system. The operating principle of each control component will be described in the following sections.

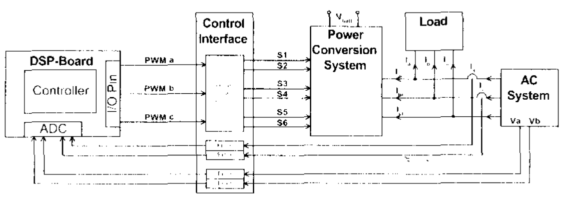


Fig. 1. The BESS control implementation

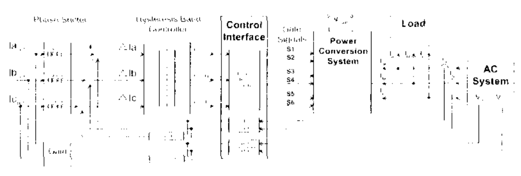


Fig. 2. The BESS control setup

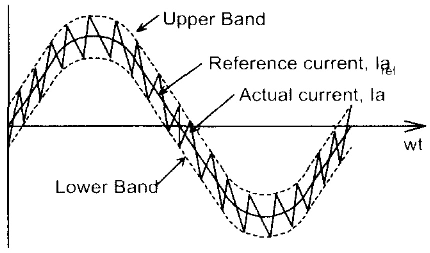


Fig. 3. Hysteresis band

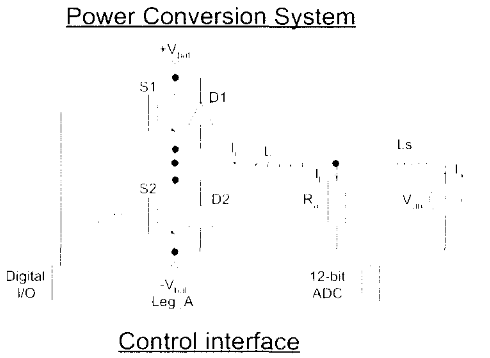


Fig. 4. Control Strategy of BESS

2.1.1 Hysteresis band controller

In this application, a hysteresis band controller is used to control the supply currents, I_a, I_b and I_c. The hysteresis band is illustrated in Fig. 3, for a sinusoidal reference current I_{aref}. The actual current, I_a, is compared with the band around the reference current associated with the correspondent phase. If the actual current in Fig. 3 tries to go beyond the upper band, S_1 is turned on (i.e., S_2 is turned off). The opposite switching occurs if the actual current tries to go below the lower band. Similar actions take place in the other two phases.

The hysteresis control of BESS is most easily interpreted if the converter is regarded as a single leg inverter. The single leg inverter, as shown in Fig. 4, represents one phase leg of the three-phase converter connected with a single-phase ac system. It shows the source current, I_a, is sampled by the 12-bit analog to digital converter (ADC). The sampled signal is then compared with a reference waveform to provide the ON and OFF signal for the IGBTs to ensure that the BESS will supply or absorb the required current to force the source current, I_a, to follow the reference waveform both in magnitude and phase. Since the reference waveform is independent of the load current (I_L), as shown in Fig. 4, the source current waveform will be kept sinusoidal, even though the load current is non-sinusoidal.

2.1.2 Phase shift controller

The phase shift controller is implemented by a programming technique called linked-list. The linked-list is a data structure consisting of a group of nodes. For instance, in an array, each data element occupies a consecutive memory location. Nodes, on the other hand, may be spread out over many different locations within memory and consists of a link field. The link field contains a pointer that shows which other node the current node is connected to. The connection of node to node forms a queue.

In this application, the length of the queue determines the angle between the supply voltage and the reference current. If the length of the queue is set, the data (the sampled supply voltage) sampled by the ADC is entered into the left-end of the queue, on the other hand, the data at the right-end of the queue will become the reference signal of the source current.

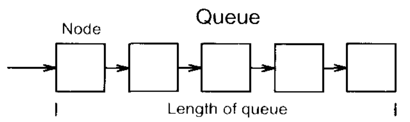
Fig. 5(a) shows that the queue is formed by connection of five nodes and Fig. 5(b) shows in each operation a new data is put into the queue with a newly created node located at the left-end of the queue. While the data at the right-end is taken away from the queue, it becomes the reference signal, and the node locating that data will be discarded. For instance, the third row of Fig. 5(b) shows the queue (five nodes) is full with data captured from ADC represented by letters a to e. When the next cycle starts, as shown in the last row of Fig. 5(b), a new data (letter f) is sampled from ADC and the data at the right-end of the queue (letter a) is taken as the reference signal. After that the node will be discarded. In this regard, it forms a time delay between the data arrived at the left-end and the data leave from the right-end of the queue. The angle shift, θ_s, is corresponded to the time delay, t_{delay}, which can be calculated as:

$$t_{delay} = Length \quad of \quad queue \times \Delta t$$

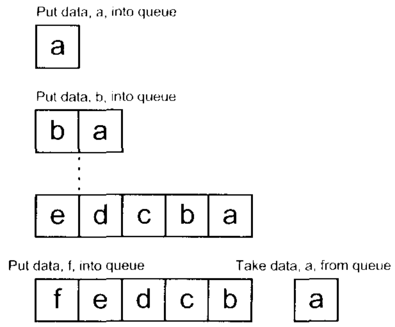
$$\theta_s = \frac{t_{delay}}{t_f} \times 360^o$$

where, Δt is the time step of each execution cycle.

t_f is the time period of a cycle (i.e. 20 msec.).



(a)



(b)

Time(sec.) (Time Step =0.00033sec)	Data Input (sampled by the ADC)	Data Shifted with an angle of 30° (0.00165sec)
T	a	X
T+0.00033	b	X
T+0.00066	c	X
T+0.00099	d	X
T+0.00132	e	X
T+0.00165	f	a
T+0.00198	g	b
T+0.00231	h	c
.	i	d
T+t		

(c)

Fig. 5. Phase Shifter operations (a) Queue (b) Queue operations (c) Time evaluation

For instance, as shown in Fig. 5(c), if the time step is equal to 0.000325 second and angle shift required is 30°. Then applying the above equations, t_{delay} can be calculated as 0.00165, and length_of_queue is finally calculated equal to 5. Fig. 5(c) shows the phase shift operation evaluated in time when 30° shift is needed, based on the calculation five buffers are formed in order to obtain the required time delay (0.00165sec.). So data 'a' is shifted from T=T to T=T+0.00165 and the above data are substituted which is represented by X.

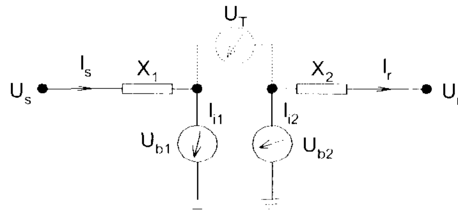


Fig. 6. Line model of the system with the SPFC (Two shunt connected BESS)

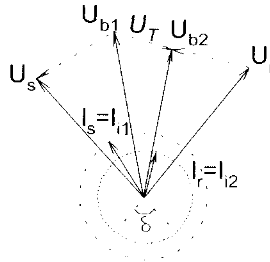


Fig. 7. Vector diagram of the system with SPFC

2.1.3 Evaluation of a storage power flow controller (SPFC)

A Storage Power Flow Controller (SPFC) consists of two BESSs connected in shunt to the grid. Each of them comprises of a hysteresis band and a phase shift controller for magnitude and phase control of a current. That means the well as to provide FACTS facilities. For instance, Fig. 6 shows the SPFC model connected at the midpoint of a line, it is represented by two shunt injection devices connected separately at the terminals of a split line. The shunt injection devices (BESSs) provide control of two currents, where control entirely of the line parameters. It provides hypothesis voltage compensation across the split line like series voltage compensation devices.

Fig. 7 shows the vector diagram of the system with the SPFC, it shows that the two currents along the lines are being controlled. And provides two current controllability for the system unlike normal FACTS devices.

From Fig. 6, Equations (1) – (4) can be written:

$$U_s = U_{b1} + jX_1 I_s \tag{1}$$

$$U_{b2} = U_r + jX_2 I_r \tag{2}$$

$$I_s = I_{i1} \tag{3}$$

$$I_r = I_{i2} \tag{4}$$

Therefore, the power flow from the source is represented by:

$$P_s = \mathrm{Re}(U_s I_l) \qquad (5)$$

$$Q_s = \mathrm{Im}(U_s I_l) \qquad (6)$$

In this evaluation, both I_s and I_l can be controlled so do U_{b1} and U_{b2}. As a result, U_L can also be controlled.

3. Implementation of the Storage Power Flow Controller (SPFC)

Before the SPFC is implemented, a single line system is shown in Fig. 8 to represent common line characteristics. Since power flow along a transmission line is a function of the sending and receiving end voltages, as shown in (7). Assuming that bus-bar magnitudes are maintained at fixed levels, in order to increase power flow, we must increase δ. However, increasing δ increases the risk of transient and voltage stability problems if a fault were to occur along the line. If both ends of the transmission line were connected to a generator, we could simply assess the post-fault transient stability conditions by using the equal area criterion and the voltage stability using AC transmission-line equations. Since power systems are far more complex then Fig. 8, so too is the problem of stability and more complicated techniques need to be sought to assess stability in highly interconnected systems.

$$P = \frac{V_1 V_2}{X} \sin \delta \qquad (7)$$

Consider a section of a power system, shown in Fig. 9. If the flows of active and reactive power from busbar V_1 to busbar V_2 in the two transmission lines are being considered, the flows are entirely determined by the line impedances and hence it is an inflexible AC Transmission System. In order to provide the required flexibility, it should be able to control the power flow in at least one of the transmission lines at high speed, faster than any fluctuations that can occur including the fluctuations due to harmonics.

Now, there is a topology in which a Battery Energy Storage System can be utilized to achieve this requirement:

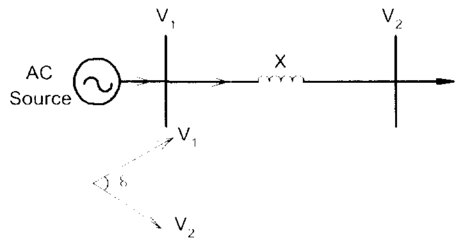


Fig. 8. Power flow along a line

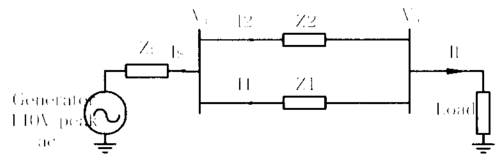


Fig. 9. A simple power system

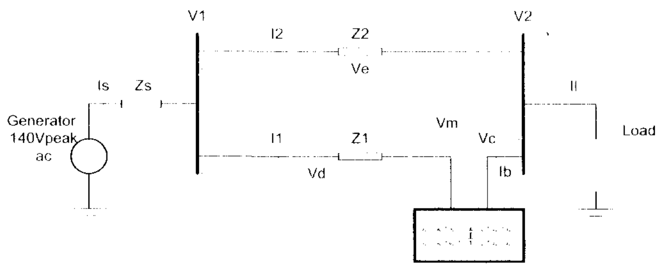


Fig. 10. The topology for SPFC

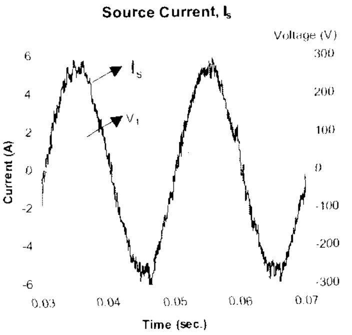
A battery bank is sandwiched between two inverters connected in series with the line is shown in Fig. 10. The two inverters are then controlled independently so that **two** independent power flows can be obtained. In this implementation, the line Z1 is split at its right end and the two BESSs, represented by the rectangular block, are inserted between the line Z1 and bus bar V2.

3.1 Controlling power flow using two BESSs, the SPFC

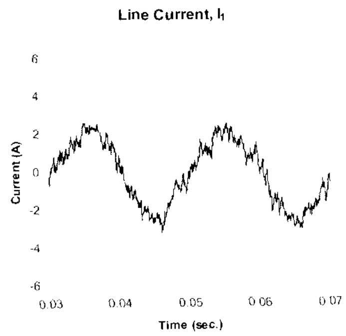
3.1.1 Experimental results of SPFC

In this configuration, we use back-to-back inverters with the BESS in the middle as shown in Fig. 10. The two inverters are then controlled independently so that **two** independent power flows can be obtained, in contrast to the conventional UPFC which can only control the power flow in **one** line only. In Fig. 10, for example, the inverter on the left controls, with high speed, the current I_1 and the inverter on the right control, with high speed, the current I_S or I_2. In this way, I_S can be quite different from I_1, the difference is supplied by the BESS. Further, I_S can be controlled to be sinusoidal and in phase with supply voltage.

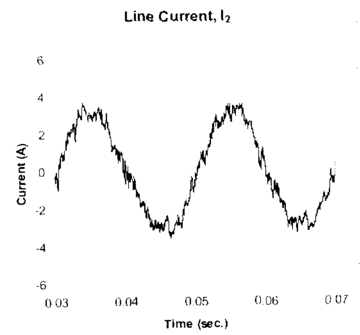
The main benefit of such an arrangement is that the battery can be charged at night by having I_S larger than I_L and during the day I_S is controlled to be smaller than I_L ensuring that the energy of battery is used to help the power system.



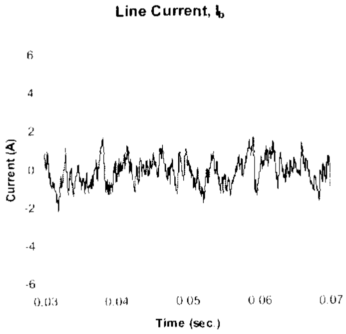
(a)



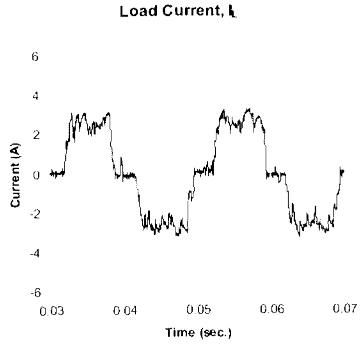
(b)



(c)



(d)



(e)

Fig. 11. Experimental results of the SPFC (a) Source Current, I_S; (b) Line Current, I_1; (c) Line Current, I_2; (d) Line Current, I_b; (e) Load Current, I_L.

Fig. 11 shows the experimental results from a laboratory implementation of the SPFC as shown in Fig. 10. To perform **two** currents control of the transmission lines, one of the converter control the source current, I_s, in phase with the bus-voltage, V_1, and the other converter control the Line current, I_2, in phase with the bus-voltage, V_1 as shown in Figs. 11(a) and (c) respectively. The difference between the currents I_s and I_2 is the current, I_1, through Line 1. In this case current I_2 is controlled almost equal to the fundamental value of the load current, I_L. Therefore, the converter at the right-hand-side provides harmonics current as shown in Fig. 11(d), required by the distorted load (Fig. 11(e)).

The topology provided by the SPFC provides the most flexible arrangement as it provides all conventional UPFC capability, while at the same provides additional benefits such as, ability to provide load leveling, provide damping of inter-area oscillations, help in damping transient stability, provide back-up electricity supply on loss of AC supply very similar to UPS applications and provide active power filtering to meet power quality standards.

4. Proof That SPFC Provides UPFC Functions

This section shows that the SPFC, shown in Fig. 10, provides the three main UPFC control functions, i.e. voltage drop compensation, phase shifting and shunt reactive power compensation. In addition, an experiment will show the actual waveforms when the two transmission lines are controlled with the same current flow through them. As long as the line currents are being controlled the same, a set of vector diagrams will show the availability of the SPFC in the three main UPFC functions.

4.1 Voltage drop compensation

For a sinusoidal load, Fig. 12(a) shows the vector diagram of V_d, V_c and V_e (see Fig. 10) when I_1 and I_2 are controlled to be equal and a half of the load current. $Z_1 = 2 \times Z_2$ in this case. Appendix 1 shows the main variables in the calculation.

Fig. 12(a) shows clearly that the voltage across the SPFC, V_e, compensates for half of the voltage drop across Z_1 represented by V_d, such that $V_d - V_c = V_e$, where V_c is the voltage drop across Z_2. This means that the SPFC acts like a continuously controlled voltage drop compensator.

4.2 Phase Angle Control

From the experiment, the values of V_1, V_2 and V_m (see Fig. 10 and Fig. 12(b)) are as follows:

$$V1 = 63.5\angle 1.79^\circ$$

$$V2 = 61.3\angle 0.43^\circ$$

$$Vm = 59.2\angle -1.02^\circ$$

From this, we can conclude that the voltage across SPFC, i.e. V_e, has shifted the angle across Z_1 from (1.79°-0.43°) to (1.79°-(-1.02°)), i.e. from 1.36° to 2.81°. This shows that SPFC acts like a phase shifter. We need to note as well that the magnitude of the voltage has changed from V_2 to V_m, so really the voltage across SPFC can be considered to be a series voltage, whose magnitude and angle can be tightly controlled at high speed. This is exactly the definition of the output voltage of the series converter of the conventional UPFC.

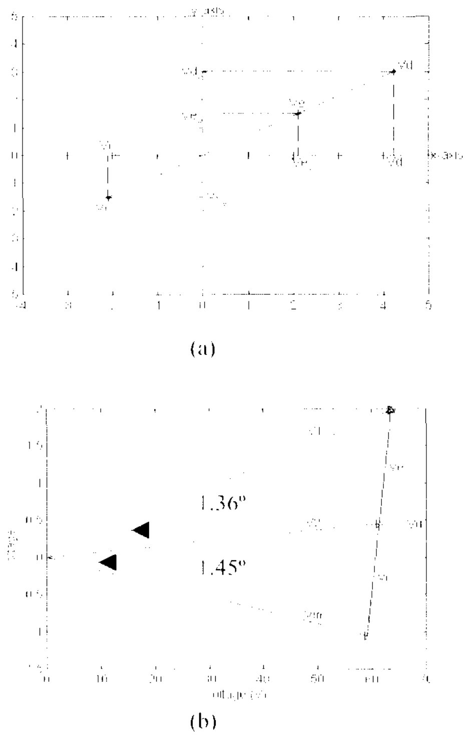


Fig. 12. (a) Vector diagram of V_d, V_c and V_e; (b) Phasor diagram of V_1, V_2 and V_m

4.3 Shunt Reactive Power Compensation

Since I_1 and I_s (hence I_2) in Fig. 10, are tightly controlled irrespective of the load current I_L, any changes in reactive power load must be compensated by the BESS, i.e. the SPFC acts like a continuously variable shunt compensation that compensates for any changes in load reactive power. Actually it compensates for any changes in active power as well, a facility which is not available in the conventional UPFC.

5. Conclusions and Discussions

This paper discusses a topology of BESS connection to the grid that provides UPFC flexibility while at the same makes use of the high-speed control of the active and reactive power of BESS to provide load leveling for energy management purposes. The paper demonstrated that the SPFC can provide all the standard functions in UPFC such as voltage drop compensation, fully controllable series voltage, both its magnitude and angle and shunt reactive power compensation. Further, it can also provide other functions not currently available in conventional UPFC. Being a static generator it can also provides back-up facility and 'negative load-shedding' or spinning reserve capability. The control strategy provides for inherent active filtering and reactive power compensation to the power system. When sufficient numbers are placed at the distribution level, the load demand seen by the transmission system can be controlled in a predetermined manner to reduce operating cost, improve load factor, provide improved power system operation and control and increase reliability of the power system, particularly, during system collapse or voltage instability. Having a single device that can provides all these facility provides for a real flexible AC system a storage form of the Power Flow Controller (SPFC).

Appendix 1

Data for the simulation in Section 4. For circuit diagram, please refer to Figure 10.

$V_s=77.78\angle 0°$;

$I_s=12\angle -10.88°$;

$Z_s=1.2+j0.0628$;

$Z_1=0.6+j0.63$; $Z_2=0.3+j0.315$; $Z_L=5+j1$;

$V_1=63.5\angle 1.79°$; $V_2=61.3\angle 0.43°$

$V_m=59.2\angle -1.02°$

$V_e=V_1-V_2=2.6\angle 35.52°$

$V_d=V_1-V_m=5.2\angle 35.52°$

$V_c=V_m-V_2=2.6\angle -144.48°$

$I_1=6.\angle -10.88°$; $I_2=6\angle -10.88°$

$I_b=6\angle -10.88°$; $I_L=12\angle -10.88°$

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