# T.1.: Design and development of active shunts for beam based alignment of beam position monitors in Indus-2 accelerator

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## Abstract

The centering of electron beam through the quadrupole magnets (QPM) of Indus-2 synchrotron radiation source (SRS) requires precise knowledge of beam position in its adjacent beam position monitor (BPM). This information is obtained by applying beam based alignment (BBA) method to Indus-2 machine. In BBA, the magnetic field of each series connected quadrupole magnet is independently perturbed through a few percent of the current of the main source by connecting an active shunt across it. The application of BBA has resulted in performance enhancement of the machine in terms of reduction in closed orbit distortion and corrector strength, ease in the availability of beam at the ports, and commissioning of insertion devices like undulator magnets. A prototype active shunt was designed and developed before its series production for this purpose. It was tested for its full load sinking and sourcing current capacity of 6 A at ±80 V. The performance of the shunt in terms of load current stability, sensitivity to disturbance, ripple, power-factor, line harmonics and power conversion efficiency was evaluated during the testing. The active shunts during their mass production underwent rigorous testing before their qualification. The active shunt caters to a dynamic load that consists of a chain of series connected QPMs, the main current source, and the active shunts across each of those magnets. Therefore, the issues concerning control, isolation, protection, switching transients and common mode interference deserved due attention. A pulse width modulated rectifier (PWMR) as the input stage of the shunt provided the regenerative utility interface augmenting the overall system efficiency and power quality. The shunt had been designed such that it supports bidirectional adjustment of quadrupole magnet strength and at the same time drawing power from the mains at unity power factor with minimum line current harmonic distortion. It was rated for ±6 A output current with a long-term stability much better than ±500 PPM of the full scale current range of the shunt.

## 1. Introduction

In a storage ring, it is important to have the electron beam trajectory as close as possible to the center of the quadrupole magnets. This minimizes the spurious orbit distortion, feed-down effects from higher order multipole components in lattice magnets, and orbit motion generated due to ripple in quadrupole magnet power supplies. Many storage rings worldwide have implemented BBA and could minimize the root mean square (rms) closed orbit distortion to the micron level [1,2].

Indus-2, a 2.5 GeV electron storage ring, has 17 operational beamlines for synchrotron radiation users including two lines for beam diagnostic applications with a beam current up to 200 mA. There are 72 QPMs in Indus-2 distributed over five families named Q1D, Q2F, Q3D, Q4F and Q5D. These quadrupole families are electrically connected in series and powered separately using 26 power supplies as per Table T.1.1.

*Table T.1.1: QPM power supplies (PSs) of Indus-2 accelerator.*

| ***Type*** | ***Current Rating, A*** | ***No. of Magnets*** | ***No. of PSs*** | ***Magnets per PS*** | ***L per Magnet, mH*** | ***R per Magnet, Ω*** |
|---|---|---|---|---|---|---|
| **Q1D** | 10 – 180 | 16 | 8 | 02 | 080 | 0.240 |
| **Q2F** | 10 – 180 | 16 | 8 | 02 | 120 | 0.330 |
| **Q3D** | 10 – 180 | 16 | 8 | 02 | 100 | 0.270 |
| **Q4F** | 10 – 180 | 16 | 1 | 16 | 100 | 0.272 |
| **Q5D** | 10 – 180 | 08 | 1 | 08 | 100 | 0.273 |

The purpose of carrying out BBA is to find out the offset between the centers of a QPM and its adjacent beam position monitor [3-5]. In the chosen scheme of BBA, it is essential to vary the magnetic field of the QPM set up by the main current source. This change in the field is achieved by connecting an active shunt across every QPM as illustrated in Figure T.1.1.

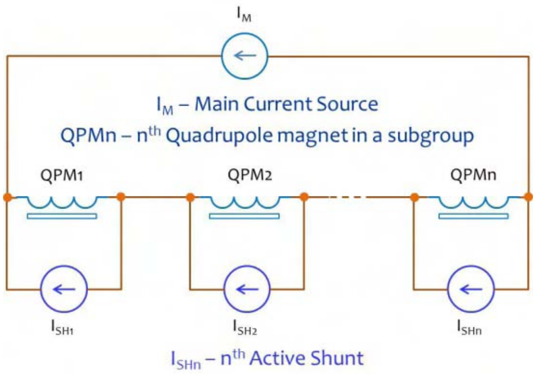


*Fig. T.1.1: Application of active shunts for modifying the magnetic field of series connected magnets; $I_M$ – Main Current Source; $I_{SH}$ – Active Shunt.*

The active shunts could have been primarily designed to facilitate the magnetic field adjustment in two ways. One way was to reduce the main field in one direction. The other way was to assist both the increase and the decrease of the main field. At Pohang Light Source (PLS) transistorized linear devices are connected across the magnets to reduce the main field [6,7]. Although the implementation of the scheme is easy, it dissipates the heat in the power devices. For the correction of the field in the bending magnets, SHUNT-20 bypass modules have been developed at Budker Institute of Nuclear Physics (BINP) [8]. In order to avoid heating in the power devices, the Fly-back topology based energy recovery scheme was used to dissipate the energy in a resistive load. This scheme had two limitations: (1) the field adjustment was limited at lower load voltages, and (2) the main field could be reduced only in one direction. The scheme used at the Brazilian Light Source (LNLS) removed the limitation of only being able to reduce the main magnetic field [9,10]. They employed a four quadrant converter at the output stage of the active shunt. When the magnetic field was reduced by the shunt, it continuously dissipated energy in a resistor connected across the DC bus with a large capacitor to avoid excessive voltage build-up. A diode was put in the circuit to protect the input stage.

The scheme described here for the active shunt overcomes the limitation of unidirectional field adjustment [11,12] and incorporates a new feature, not used elsewhere for this application, to efficiently handle the energy absorbed from the magnet by employing bidirectional utility interface. This interface achieves unity power factor operation with lower line current harmonic distortion.

This article broadly discusses the various components of the BBA, viz. the methodology, BPMs, control architecture and, particularly, the active shunts in detail.

## 2. Beam based alignment

In the third-generation light sources like Indus-2, any small misalignment of the beam in the magnetic elements can seriously affect the machine performance and impact one's ability to model the machine behaviour. Thus, the alignment of QPMs in accelerator is very much essential to achieve the optimum performance. The standard mechanical alignment between the magnetic center of QPM and the electrical center of its adjacent BPM is limited due to physical activities in the vicinity of magnetic elements during machine maintenance and drift in the offsets of BPM processing electronics over long time. The BPM that measures the transverse positions of electron beam in horizontal and vertical planes shall have to be perfectly aligned with its nearest QPM, so that proper information of closed orbit distortion (COD) can be acquired. Even if a good quality mechanical alignment is carried out in an accelerator, there remains an offset between the electrical center of the BPM and the magnetic center of a neighbouring QPM, which is known as BPM offset as shown in Figure T.1.2. In order to obtain a fine COD correction, prior information of BPM offset is utmost important.Using the technique of BBA in which the beam itself is used as an alignment tool, these offsets can be determined. These offsets allow us to make the beam pass through magnetic center of all QPMs. When the beam passes through the magnetic centers of the QPMs, it helps the machine operation in following ways: (a) QPM doesn't generate any orbit distortion, as the magnetic field at its centre is zero, and (b) the amount of orbit distortion caused by power supply ripple will be minimized. The BBA approach has been applied [2] for finding the BPM offset in many storage rings such as ALS, SOLEIL, PLS, SLS, SSRF, etc. This technique measures the BPM offset with highest precision.

### *2.1. Working principle of BBA*

In this technique, the beam orbit is steered through the QPM adjacent to a BPM using a most effective corrector magnet in steps, and the magnetic strength of QPM is varied by $\pm\Delta k$ over the nominal value of QPM strength $k$ for each step to ascertain that the beam is passing through center of QPM. The most effective corrector magnet for each QPM-BPM pair is estimated using measured response matrix analysis, which gives maximum orbit variation at the QPM location with minimum change in corrector strength. This BBA technique requires a provision to change the strength of QPM individually. Thus, the active shunt was designed with strength of 6 A, which is about 3% of main QPM strength at its peak value. The algorithm for this BBA defines a merit function as mentioned in Eq. (1) and minima of this function signifies that the beam is passing through the center of the QPM [13].

$$f_\theta = \frac{1}{N}\sum_{i=1}^{N}\left(x_i(+\Delta k) - x_i(-\Delta k)\right)^2 \qquad (1)$$

Where, $\theta$ is the strength of corrector magnet; $N$ is the number of BPMs in the ring and $x_i(\Delta k)$ is the change in COD after changing the strength of quadrupole by $\Delta k$. The merit function '$f$' is evaluated for different values of corrector strength ($\theta$) to find the offset of the BPM. An offset of one such BPM (LS4BPI1B, a BPM in Indus-2 ring) in horizontal plane is shown in Figure T.1.2. The estimated BPM offset is -0.5 mm in horizontal plane. Likewise, offset of all the 62 BPMs installed in Indus-2 distributed along the circumference of storage ring were estimated with the use of the active shunts and the control automation.

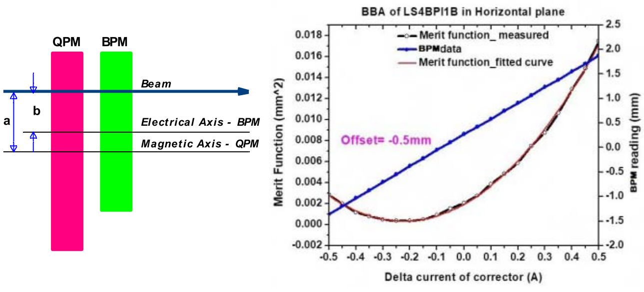
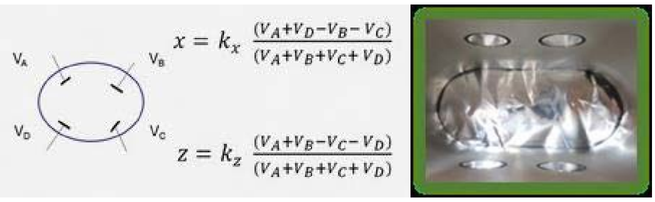


*Fig. T.1.2: Working of BBA, offset: b-a.*

With the incorporation of BPM offsets determined through BBA into the BPM system, the rms COD in Indus-2 could be corrected to 0.45 mm from 1.3 mm in horizontal plane, and to 0.2 mm from 0.43 mm in vertical plane [13], the rms value of the corrector magnets' strength used after COD correction came down to 1.4 A from 3.5 A in horizontal plane, and to 1.4 A from 2.6 A in vertical plane. It also resulted in increase in beam lifetime due to increased aperture becoming available to the beam. Apart from BBA, the active shunts will also be used for linear optics correction of the storage ring from closed orbits.

### 3. Beam position measurement system

The BPM used in Indus-2 has four button electrodes with a diameter about a centimetre, which grabs the beam signal on the principle of capacitive pick-up. The amplitude of the pickup signal is proportional to the beam proximity. These electrode signals, as shown in Figure T.1.3., are used to obtain horizontal and vertical beam positions.



(a) (b)

*Fig. T.1.3: (a) Principle of a 4-electrode BPM (Electrode potentials: $V_A$, $V_B$, $V_C$, and $V_D$; Constants: $k_X$ and $k_Z$ ) and (b) photograph of 4-electrode BPM installed at Indus-2.*

All these BPMs have been calibrated in the laboratory using an RF signal replicating the beam pick up before their installation in Indus-2 accelerator [3,4]. Also, after the installation of the BPMs in the Indus-2 ring, the alignment errors with respect to magnet axis and RF cable attenuation connecting the four electrode signals to the processing electronics have been measured. The obtained data are used to apply appropriate corrections to beam position calculations. However, for further correction in the beam position data, there is a requirement to calculate the BPMs' gain and offset using orbit response matrix and BBA, respectively. The slow orbit feedback (SOFB) system uses 56 BPMs out of the 62 BPMs in the ring to maintain the beam orbit within ±30 µm from the desired beam orbit (Golden Orbit) [5].

### 4. Active shunt: Design objectives and issues

The active shunts were expected to meet the following goals through their design: (1) They should be capable of reducing or increasing the magnet current over the full operating range of the main current source, $I_M$, as shown in Figure T.1.4; (2) they should provide at least ± 3% change in the field of QPM; (3) the beam already present in the machine should not get disturbed due to turn 'ON' and turn 'OFF' transients; (4) they should be isolated from the magnets and other circuit elements when in 'OFF' state; (5) sufficient isolation must be provided where the number of series connected QPMs is higher; (6) in the long chain of series connected QPMs, the active shunts, the main current source and the magnets form a complex dynamic system, so, it should mitigate the influence of the active sources on one another in the same circuit; (7) a system should exist for the efficient handling of the magnetic energy absorbed by the shunt; and (8) they should have provision for the feed-forward compensation to meet load disturbance.

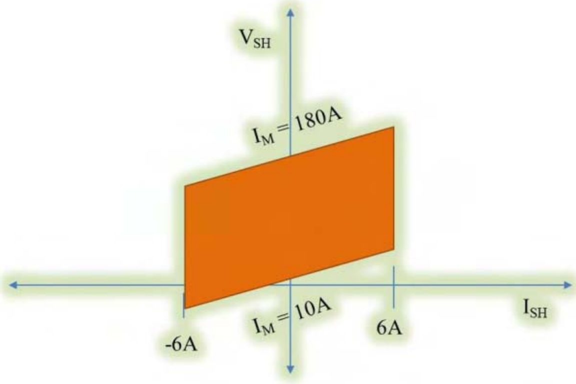


*Fig. T.1.4: Multi-quadrant operation of active shunt as a function of main current source IM of QPM.*

### 5. Active shunt: Powering scheme

A powering scheme fulfilling the design objectives of the active shunt was developed in two stages. The output stage was made of a four quadrant converter (FQC), so that the shunt could sink or source current from the QPM throughout the operating range of the machine [11]. If a proper utility interface was not provided, the power received from the load would have had to be dissipated in a resistor.

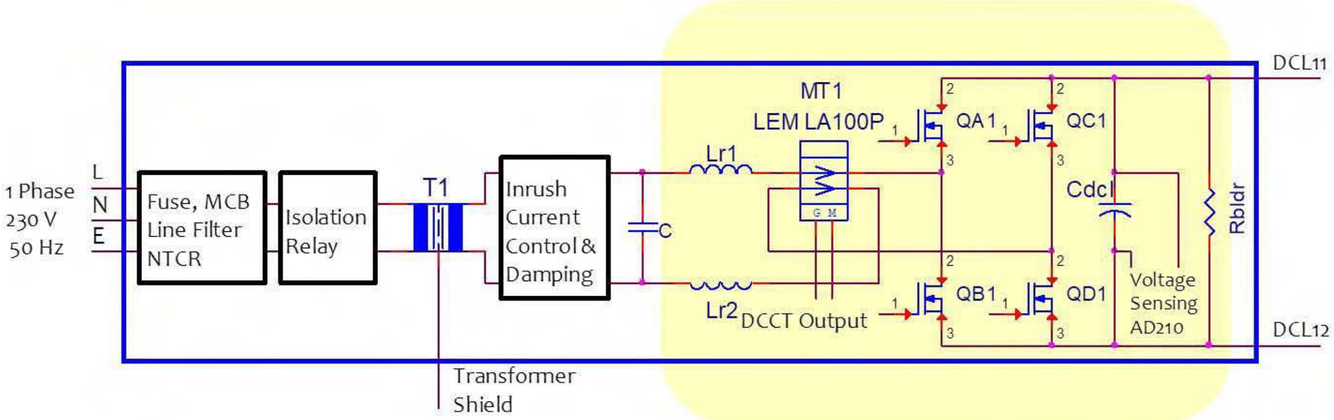


*Fig. T.1.5: Input stage of the active shunt built with a pulse width modulated rectifier.*

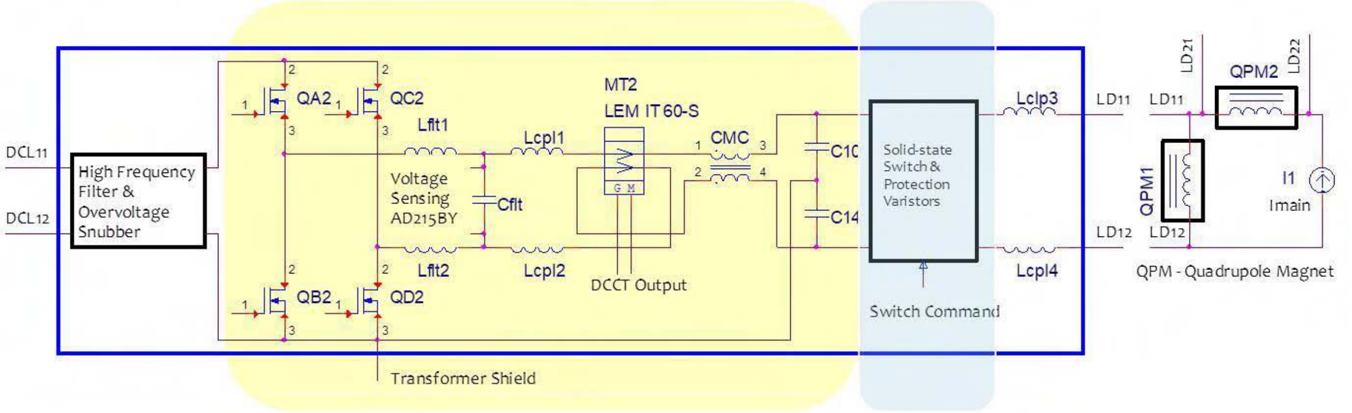


*Fig. T.1.6: Four quadrant converter at the output stage with a solid-state switch.*

Instead, a converter supporting bidirectional flow of power could provide an energy efficient utility interface. A PWMR, used here as the shunt input stage, provided the two-way utility interface due to its ability to function as both a rectifier and an inverter [14].

### *5.1. Input stage – PWMR*

The PWMR bridge, as shown in Figure T.1.5., uses IXYS make IXFK140N30P MOSFETs. The bridge switches at 25 kHz with unipolar switching scheme (USS) [15]. A film type DC link capacitor of 1 mF value is connected across the output. The output voltage across this capacitor is maintained at 100 V by a control loop. The output voltage is sensed with an isolation-amplifier, AD210, and the input current with a LEM make current transducer, LA100P. The input stage receives power from the mains through a single-phase step-down transformer. The secondary of the transformer is connected to the bridge through two separate coupling inductors of 1 mH, which are placed on either line of the secondary. These inductors offer balanced common mode impedances to the circuit. A small capacitor across the secondary winding of the transformer provides a path for the circulation of high frequency currents generated in the PWMR. The peak value of the transformer secondary voltage has to be less than 70 V at the maximum line voltage for the proper operation of the PWMR. Typical power loss in the MOSFET H-bridge is less than 50 W at 500 W of output power.

### *5.2. Output stage – FQC*

The output stage as depicted in Figure T.1.6 delivers ±6 A current at ±80 V. An H-bridge switching at 50 kHz is employed here to facilitate multi-quadrant operation of the shunt. The same MOSFETs are being used here that have been used in the PWMR. They have lower 'ON' resistance, which reduces the conduction loss. The total power loss in the MOSFET bridge is less than 25 W while catering to a 500 W load.

The main advantage of using USS control here is that the switching ripple frequency becomes twice that of the MOSFET switching frequency, which reduces the filter size. The output of the FQC is smoothened with a second order filter having 10 kHz cut-off frequency. The four coupling chokes in the output stage minimize start-up current transients. Their balanced arrangement restricts the flow of the common mode currents from the magnet and the main current source to the active shunt and vice versa. The conducted electromagnetic interference (EMI) flowing towards the mains due to the switching circuits associated with the FQC and the PWMR is controlled by connecting the lower end of the DC bus to the transformer shield placed between the primary and the secondary windings. The output current is sensed in a differential manner with a precision current sensor for reducing the error due to the common mode currents.

A four-quadrant solid-state switch isolates the load from the shunt when it is put off. The switch is realized with two series connected MOSFETs such that their source terminals get shorted. The load current always passes through: (1) one of the two MOSFETs and (2) the parallel combination of the remaining MOSFET and its antiparallel diode independent of the direction of the load current. The roles of the MOSFETs are exchanged with the reversal of the load current. The MOSFET with its antiparallel diode, conducting together in the solid-state switch as a synchronous rectifier, cuts the power loss in the switch.

Before the solid-state switch is opened, the output current is brought to zero by setting its control loop reference. Though the current remains very close to zero, the non-zero magnitude of the current will have some magnetic energy stored in the coupling chokes and the magnet. This energy would have caused a voltage spike to appear across this switch, if metal oxide varistors (MOV) were not put in this switch circuit to clip the voltage and absorb the energy.

The input DC bus gets shorted twice in a switching cycle whenever current commutates from an antiparallel diode of a MOSFET to the other MOSFET of the same leg in the bridge. The reverse recovery of the diode at the end of the commutation generates a severe voltage spike across the H-bridge of the FQC. To reduce the intensity of the voltage spike, an over-voltage snubber has been placed very near across the bridge.

## 6. Active shunt: Control scheme

The total system is required to be operated smoothly in a controlled manner during transient conditions and steady-state. It should not cause undesired jerks to the beam already present in the Indus-2 ring. The system is put ‘ON’ and ‘OFF’ in a time coordinated sequence. The controllers used in the input and output stages must guarantee the system performance.

### *6.1. Overall control*

Initially, the main relay of the circuit is operated to connect the mains to the transformer. The DC link capacitor at the output of the PWMR stage is charged slowly through a resistor to the peak value of the transformer secondary voltage. The charging resistor is bypassed after a fixed delay, and then the PWMR gating signals are released. Next, the PWMR output voltage is maintained at the desired value by a control loop. Afterwards, the gate signals to the FQC are released operating it in a voltage control mode with the zero-voltage reference and then the output voltage of the FQC is brought close to the load voltage in a controlled manner. Thereafter, the shunt is connected to the magnet by closing the load-switch and simultaneously the current loop is made active with its reference maintained at zero. Due to the fast response of the solid-state switch, the current loop controller output does not shoot up abruptly pushing the voltage loop controller to go into saturation. This ensures minimum disturbance to the load during turn ‘ON’. Finally, the shunt tracks the actual current reference slowly to the final value. During turn ‘OFF’ operation, first the shunt current is brought to zero. Then the gate signals to the FQC and the load-switch are withdrawn. Finally, the PWMR is put ‘OFF’. The time-coordinated events of the active shunt have been realized with discrete digital logic gates, timers and flip-flops.

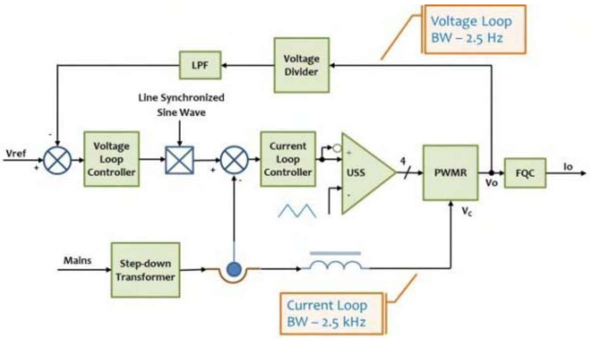


*Fig. T.1.7: Block diagram of input stage – PWMR.*

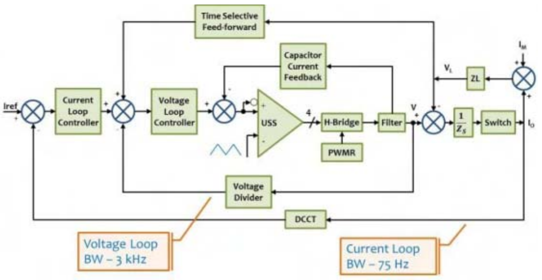


*Fig. T.1.8: Block diagram of output stage – FQC.*

### *6.2. PWMR control*

There are two control loops, as shown in Figure T.1.7, which determine the PWMR operation. The output voltage across the DC link is maintained at the desired voltage by the outer control loop. The error voltage at the output of the voltage loop controller is multiplied by a stable sine wave of unit amplitude derived from the line voltage. The amplitude of the sine wave thus obtained after the multiplication generates a reference for the inner current loop. This reference is then compared with the transformer secondary current. The error obtained after the comparison is processed further by the current loop controller to force the input current to be sinusoidal. The magnitude of the current depends on the power fed into or absorbed from the load circuit. The PWMR with input transformer works near unity power factor over wide operating range except at light loads when the magnetizing current of the transformer starts dominating the load component in the line.

### *6.3. FQC control*

The MOSFET switching control in the FQC is achieved using USS. The outermost control loop of the FQC as shown in Figure T.1.8 regulates the load current. Here, the load current regulation is crucial due to the two reasons: firstly, the load current gets disturbed due to the load voltage changes that occur when the main current source is changed and then, secondly, due to the ambient temperature variation. The current loop controller output provides reference to the inner voltage loop. The voltage loop provides fast correction in the output voltage against the variations in the input voltage to the FQC. It also reduces the nonlinearity in the transfer curve of the FQC, when the output voltage is close to zero, due to the finite dead-times provided in the gate drive circuit to avoid shoot-through. It also offers an injection point for the addition of feed-forward voltages along with the feedback system. It could be used to improve the dynamic response of the active shunt against the known disturbances.

*Table T.1.2: Performance of active shunt at full power multi-quadrant operation.*

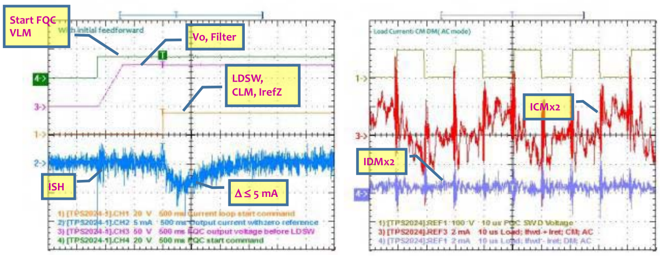
| ***Parameter*** | ***Value achieved*** |
|---|---:|
| Stability (drift, regulation) | Better than ±50 PPM |
| Differential mode current (ripple) | < 25 PPM |
| Common mode current | < 100 PPM |
| Sensitivity (active shunt to $I_M$) | ~ ±5 PPM |
| Sensitivity ($I_M$ to active shunt) | ~ ±6 PPM |
| Turn ‘ON’ transients | < 500 PPM |
| PWMR voltage loop bandwidth | ~ 2.5 Hz |
| PWMR current loop bandwidth | ~ 2.5 kHz |
| FQC voltage loop bandwidth | ~ 3 kHz |
| FQC current loop bandwidth | ~ 75 Hz |

## 7. Active shunt: Performance

The performance of the prototype active shunt was assessed by connecting to Q4F QPMs of Indus-2 accelerator and tested during the machine operation. The remaining 79 units were tested in the laboratory [16] prior to their commissioning at Indus-2 accelerator complex. The summary of performance of the active shunts is given in Table T.1.2 and Table T.1.3. A few important waveforms shown below are as follows: (1) Turn 'ON' current disturbance, Figure T.1.9(a), (2) Ripple current, Figure T.1.9(b), and (3) Line current waveform and its harmonic content, Figure T.1.10.

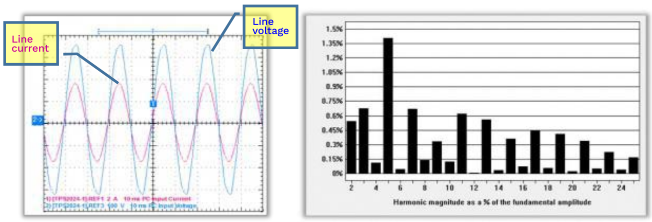
*Table. T.1.3: Performance of active shunt at full power multi-quadrant operation (AS#72).*

| *Mode of operation* | *Transformer Primary* | | | | | | *THD-F* | | *Output Voltage* | | | *Power Transfer Efficiency (%)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Voltage RMS, V | Current RMS, A | True Power, W | Reactive Power, VAR | Phase Angle, degree | DPF | THD-V, % | THD-I, % | Voltage DC, V | Current DC, A | Power, W | |
| Quad I | 232.90 | 2.32 | 546.00 | 10.70 | 1.13 | 1.000 | 2.10 | 1.90 | 80.05 | 5.01 | 401.1 | 73.5 |
| Quad II | 235.00 | 1.36 | -320.00 | 24.10 | 175.70 | -0.997 | 2.03 | 4.71 | 80.02 | -5.00 | -400.1 | 80.0 |



(a) (b)

*Fig. T.1.9: (a) Disturbance in active shunt current, Wfm.2.Blue (5 mA/div), at the closure of current loop (initial feed-forward maintains the input and the output voltages of the load-switch to be neck to neck prior to its closure.), (b) active shunt load current: AC CM current, Wfm.3.Red (2 mA/div) (2xICM: forward plus return current); AC DM current, Wfm.4.Purple (2 mA/div) (ripple current) (2xIDM: forward minus return current).*



(a) (b)

*Fig. T.1.10: Line side performance of active shunt operating in the first quadrant (Load voltage/current – 76 V / 6 A); (a) line current, Wfm.1.Pink (2 A/div), and line voltage, Wfm.2.Blue (100 V/div), and (b) line current harmonics, THDi ~ 2.18 %.*

A photograph of the test set-up developed in the laboratory is shown in Figure T.1.11.

*Fig. T.1.11: A laboratory test facility showing the active shunt, dummy magnet load and main current source; and a cabinet containing four active shunt units with a control rack on one side.*

## 8. Control system for BBA

The control system for the BBA primarily requires manoeuvring of the currents of the active shunts and the corrector magnet power supplies, capturing the readings of the BPMs and, finally, processing the data to arrive at the BPM offsets in vertical and horizontal planes. This was achieved through the development based on the standard three-layer control system used at Indus-2 and by providing all the features in the hardware and software similar to that being used for the magnet power supplies' control of Indus-2 accelerator. A software module developed for this purpose automates the sequence of operation for the BBA. The active shunts were interfaced at the equipment interface layer of the control system. This is a Versa Module Eurocard (VME) based system, which provides stable bipolar reference signal and records read-back with 16-bit accuracy. The GUI based control system software, as shown in Figure T.1.12, was developed for monitoring, reference setting, and data logging with alarm functions.

1.518713 Tesla

DCCT Current: 115.98 mA Beam Energy: 2.499 GeV

QP SHUNT Magnet PS -- Indus-2

| | Name | R/L | Ld_on/off | Set_Value | Readback | Mode |
|---|---|---|---|---|---|---|
| #1 : HB-1 | PS-1 (AS08 A) | LOC | OFF | 0.00 | 0.044 | DC |
| #2 : HB-1 | PS-2 (AS08 B) | LOC | OFF | 0.00 | 0.058 | DC |
| #3 : HB-1 | PS-3 (AS08 C) | LOC | OFF | 0.00 | 0.061 | DC |
| #4 : HB-1 | PS-4 (AS08 D) | LOC | OFF | 0.00 | 0.064 | DC |
| #5 : HB-2 | PS-5 (AS09 A) | LOC | OFF | 0.00 | 0.067 | DC |
| #6 : HB-2 | PS-6 (AS09 B) | REM | OFF | 0.00 | 0.075 | DC |
| #7 : HB-2 | PS-7 (AS09 C) | REM | OFF | 0.00 | 0.051 | DC |
| #8 : HB-2 | PS-8 (AS09 D) | LOC | OFF | 0.00 | 0.065 | DC |
| #9 : HB-3 | PS-9 (AS02 A) | REM | OFF | 0.00 | 0.048 | DC |
| #10 : HB-3 | PS-10 (AS02 B) | REM | OFF | 0.00 | 0.052 | DC |
| #11 : HB-3 | PS-11 (AS02 C) | LOC | OFF | 0.00 | -0.003 | DC |
| #12 : HB-3 | PS-12 (AS02 D) | LOC | OFF | 0.00 | -0.003 | DC |
| #13 : HB-4 | PS-13 (AS03 A) | LOC | OFF | 0.00 | -0.002 | DC |
| #14 : HB-4 | PS-14 (AS03 B) | REM | OFF | 0.00 | -0.001 | DC |
| #15 : HB-4 | PS-15 (AS03 C) | REM | OFF | 0.00 | -0.003 | DC |
| #16 : HB-4 | PS-16 (AS03 D) | LOC | OFF | 0.00 | -0.000 | DC |
| #17 : HB-5 | PS-17 (AS10 A) | LOC | OFF | 0.00 | -0.004 | DC |
| #18 : HB-5 | PS-18 (AS10 B) | REM | OFF | 0.00 | -0.004 | DC |
| #19 : HB-5 | PS-19 (AS10 C) | REM | OFF | 0.00 | -0.001 | DC |
| #20 : HB-5 | PS-20 (AS10 D) | LOC | OFF | 0.00 | -0.004 | DC |

Readback Current: 0.04 Amp

Mode: DC

Range: 10
Max: 8
Min: -6
Polarity: BiPolar
Accuracy: High
Bc slope: 2

DC Set: 0.000

Set_Inc/Dec Amount: 0.5

Info: Command could not be sent as Power Su

*Fig. T.1.12: GUI for the operation and monitoring of active shunt.*

## 9. Conclusion

The active shunts have been a vital tool for performing BBA in Indus-2 accelerator. Incorporating the BPM offsets determined through BBA using control automation into the BPM system, the rms COD in Indus-2 could further be reduced, and the required strength of the corrector magnets got minimized improving the beam lifetime due to the availability of increased aperture to the beam.

The active shunts have been designed such that they do not cause loss of electron beam inside the vacuum chamber because of switching 'ON' and 'OFF' transients. The observed current stability and the ripple are within the required specifications. They meet the design specification of sinking/sourcing power from/to the load. Whenever the shunt draws power from the load, it is fed efficiently into the mains. The PWMR used as the input stage of the shunt achieves lower line current harmonic distortion maintaining the input power factor close to unity over wide operating current range. Moreover, the regenerative mode of the PWMR has not only provided a greener utility interface with efficient energy recovery, but also helped in significantly reducing the cooling load of the shunt.

The active shunt employs two switching stages, PWMR and FQC, which slightly reduces the overall efficiency. But, the efficiency can further be improved by optimizing the design of the magnetic components and using MOSFETs with lower Rds(On). The application of common mode filters, balanced circuit arrangement and transformer shield have helped keeping the flow of common mode current to a reasonable value. The present scheme is somewhat space demanding for accommodating the magnetics and the additional control circuitry required for the PWMR.

Eighty units of the active shunt based on the above design have been fabricated in-house and placed in twenty cabinets, as shown in Fig.T.1.11, and they are being regularly used in the Indus-2 accelerator for the BBA exercise.

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