International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 11 | Nov 2021 www.irjet.net p-ISSN: 2395-0072

DC System Design Comparison and Future Technologies Consideration – A Utility Perspective

(Why We Did What We Did)

Syed Fahim Ahmed[1], Alaa Magdi Ali[2], Noora Jamal Ahli[3], Sana Zargham Ziaei[4]

[1]Sr. Engr.-Trans. Prot. Engg., DEWA, UAE
[2]Engr.-Trans. Prot. Engg., DEWA, UAE
[3]Engr.-Trans. Prot. Engg., DEWA, UAE
[4]Dy. Mngr.-Trans. Prot. Engg., DEWA, UAE

---***---

Abstract – *DC system is considered as the heart of control and protection in power system. Choosing an optimum DC system for a utility may sound simple enough, however, utilities need to go through their requirements and use their experience extensively in order to find the right solution. The purpose of the authors of this paper is to share their journey and experience in designing and choosing a DC system for transmission substations in one of the largest utilities in the Middle-East Dubai Electricity & Water Authority (DEWA).*

Key Words – Direct Current (DC) System, Alternate Current (AC) System, Power System, Battery, Charger, Protection System, Dubai Electricity & Water Authority (DEWA)

1. INTRODUCTION

Although the modern day power system is dominated by AC systems, the first large scale central electric power generating station was in fact DC based. In 1882, Thomas Alva Edison built a DC power generating station at Pearl Street in New York [1]. This was a 100kW installation. In the subsequent years, similar models were being established in the cities across the globe. The initial dominance of DC in power system came under challenge with the advancement of AC technology in mid-1880's. Nicola Tesla, Michael von Dolivo-Dobrowolsky, Lucien Gaulard and other inventors contributed greatly towards the development of AC technology. Arguably, the most important factor that may have contributed in establishment of AC dominance was the invention of the AC induction motor in 1888 [2]. This has truly demonstrated the use case of AC power. In the subsequent years, the development of transformers and 3-phase system ensured that AC will become the dominant force in power system in the foreseeable future.

DC system may have lost its dominance to AC system over the time, but its importance has never abated even a little bit. In fact, DC is gaining more and more prominence with the advancement of renewable energy, electric cars, electronic devices etc. The fact that DC can be stored via batteries, this gives it unique and critical use cases that AC can never achieve. Therefore, establishing a robust and reliable DC system is integral part of any utility strategy.

The main elements of substation DC systems are:

- Battery
- Charger / Rectifier
- **DC D**istribution **B**oard (**DCDB**)

There are also other auxiliary components like input transformers, battery fuses, isolators, circuit breakers, blocking diodes, MCBs, filters etc. that is present in complete DC systems. However, we would like to limit our focus on the items specified above.

2. TYPE OF BATTERIES

There are number of options available when it comes to choose the type of battery. Each type has its own advantages and disadvantages. The utility must look at its requirements and choose the best one it sees giving the most benefit. In this chapter the authors would like to go through 3 main different types of batteries that are being widely used in power system.

2.1 Vented or Flooded Lead Acid Batteries

Vented Lead Acid Batteries are one of the most widely used batteries in power system. Vented Lead-Acid batteries are basically comprised of PbO_2 as positive plate, Sponge Pb as negative plate and diluted H_2SO_4 as electrolyte. Separators are place between positive and negative plates to avoid physical contacts. The popularity of Vented Lead-Acid battery primarily derives from its low initial cost as well as moderate life time maintenance cost. It also generally enjoys higher life span than Valve Regulated Lead Acid (VRLA) batteries.

2.2 Sealed Maintenance Free or Valve Regulated Lead Acid (VRLA)Batteries

Valve Regulated Lead-Acid batteries are completely sealed and do not require any top up of electrolytes. Each VRLA battery cell has a pressure relief valve. This valve is activated by battery internal pressure developed due to Hydrogen gas. This happens when the battery is being recharged.

There are mainly 2 types of VRLA batteries available – Absorbent Glass Mat (AGM) and Gel Battery. In AGM type VRLA battery, the electrolyte is Fiberglass Matt type whereas in Gel battery, the same is gel type. Due to extremely low gas and acid output, VRLA batteries are much safer to use in indoor applications. In addition to that, this battery can be used in any arrangement e.g. horizontal or vertical depending on the requirement. VRLA batteries are widely used in UPS system, automobile, power wheelchairs etc.

2.3 Nickel-Cadmium Batteries

Nickel-Cadmium (Ni-Cd) batteries are gaining more and more popularity for power system applications. Ni-Cd battery uses Nickel Hydroxide [$Ni(OH)_4$] as positive plate and Cadmium (Cd) as negative plate. The electrolyte used for Ni-Cd battery is Potassium Hydroxide (KOH). The big difference on Ni-Cd battery with Lead-Acid battery is that the plates do not react with the electrolytes. There are different designs available for Ni-Cd batteries. The most common design is Pocket Plate type. There are other Ni-Cd designs such as Fiber Nickel-Cadmium etc. which are also commercially available.

3. THE FACTORS CONSIDERED IN CHOOSING THE BATTERY TYPE

3.1 Reliability

Although Vented Lead-Acid batteries may perform beyond 10-15 years with proper maintenance, these are highly susceptible to Sudden Death or Open Circuit. In short, any single cell damage may lead to loss of entire battery system. On top of this, Valve Regulated Lead Acid (VRLA) battery could suffer some unique failure modes such as Dry Out, Thermal Runaway, Negative Strap Corrosion [3] etc. Any loss of DC system could lead to a catastrophic outcome in power most notably non-operation of protection system during actual fault. Ni-Cd batteries are not exactly 100% flawless, however, the failure mode is basically short circuit. In short if one of the battery cell is faulty it will simply be shorted which means we will lose only that particular battery cell instead of entire bank like Lead-Acid batteries. Clearly Ni-Cd batteries are by nature most robust and more reliable than Lead-Acid batteries. Dubai being one of the most prominent business hub of the world, maintaining constant and reliable power supply is imperative a having a reliable DC supply is integral part of achieving that goal. Ni-Cd could just give what a utility like Dubai Electricity & Water Authority is looking.

3.2 Life Cycle

As mentioned earlier, typical life cycle of Vented Lead-Acid battery is 10-15 years. Interestingly enough, even though Valve Regulated Lead Acid (VRLA) batteries are touted as maintenance free; the typical life cycle of VRLA battery is actually less than that of Vented Lead-Acid battery typically 3-5 years, in exceptional cases may go up to 10 years. In case of Ni-Cd batteries, a well planned maintenance can extend the life beyond 20-25 years. So considering life cycle length, Ni-Cd batteries clearly have an advantage over the Lead-Acid batteries.

3.3 Performance with Respect to Temperature Variation

Being a utility in MINA (Middle-East & North Africa) region, temperature is always a huge factor which is needed to be considered in designing everything including batteries. Different studies [4]clearly shows that the performance of Lead Acid Battery is hugely impacted by temperature. Although substations in DEWA are air conditioned and designed to keep the temperature on or about 25°C, there is always possibility of Air conditioning failure or maintenance. In worst case scenario, any air conditioning failure during summer can lead to substation interior temperature close to ambient temperature which could be as high as 50°C. The thumb rule suggests [5] [6]that every 8°C (15°F) increase in operating temperature above 25°C reduces the life cycle of Lead-Acid batteries by 50% whereas the same temperature increase will reduce the life cycle of Ni-Cd batteries by 20% only.

3.4 Maintenance Cycle / Frequency

One of the most important factor that a utility like DEWA where a large number of substations are unmanned, would need to consider is how often or how frequently the batteries need to be inspected or maintained. IEEE standards 1188 [7] 8, 450 [8] and 1106 [9] give us the recommended inspection frequencies of VRLA, Vented Lead-Acid (VLA) and Ni-Cd batteries respectively. The following table summarizes the maintenance requirements [7] [8] [9] of above 3 types of batteries in brief:

Maintenance Type	VRLA	VLA	Ni-Cd
Visual Inspection	Monthly	Monthly	Quarterly
Float Voltage Measurement	Monthly	Monthly	Quarterly
Individual Cell Voltage	Quarterly	Quarterly	Biannual
Electrolyte Level	Never / Replace	Monthly	Quarterly

The above table clearly indicates that Ni-Cd batteries generally require less frequent maintenance than Lead-Acid batteries. Therefore, it can be an ideal choice for a utility like DEWA.

3.5 Cost

Ni-Cd batteries have by far the highest initial cost among the 3 types being discussed. However, there are indirect costs involved with Lead Acid batteries that may in fact far exceed the life cycle operating cost of Ni-Cd batteries. First of all, Lead-Acid Batteries need more frequent maintenance / inspection; clearly this will incur more manpower cost. Secondly, Lead-Acid batteries have shorter life cycle, therefore, needed to be replaced more frequently. Last and perhaps most importantly, the reliability factor. Even with the best of maintenance plan, Lead-Acid batteries are prone to sudden death or open circuit leading to loss of entire battery bank. The cost of any non-operation of protection device during a fault (due non availability of DC) could lead to severe equipment damage as well as loss of human lives.

Considering all the factors mentioned above, clearly Ni-Cd battery was a logical choice for DEWA.

4. SELECTION of NICKEL-CADMIUM BATTERY DISCHARGE CHARACTERISTICS (L, M, H or X Type)

Once we were fixated to Ni-Cd battery for substation applications, next step was to select the type of discharge characteristics needed. IEC60623 [10] defines 4 (four) different types of Ni-Cd batteries in terms of discharge characteristics:

a) L type (Low rate of discharge)
b) M type (Medium rate of discharge)
c) H type (High rate of discharge)
d) X type (Very high rate of discharge)

In order to select the required type of battery discharge characteristics, first we need to understand what are the applications and characteristics of each types. X type batteries have ultra-thin electrodes and are by definition, designed to provide very high output or discharge for a short duration. The main application for X type batteries are start of the engine and UPS system. H type is also designed to provide high output for a short time but not as extreme as X type. The main application for H type battery is UPS system, start of the engine and switchboards. The typical discharge time for X & H type batteries ranges from few seconds to 30 minutes. M type batteries are designed to supply medium rate of output for moderate time duration typically ranges from 30 minutes to 2 hours or more. The main applications of M type batteries are emergency power supply and switchboards. Finally, L type batteries are designed to supply load with long discharge time ranging from 1 hour to 100 hours. Discharge current is low compared to total stored energy. The typical application for L type batteries are emergency power supply, switchboard, reliable long term energy storage etc.

When we analyze the DC load pattern in the substations, it is more or less flat without much variations. One exception may be a very rare case of Busbar protection operation where dozens of circuit breakers may operate and subsequently motor charging of those operated circuit breakers commences. The typical required backup time of DC system in a substation is expected to be several hours. The backup time should be sufficiently long enough for the maintenance team to be able to reach the substation and restore the system. While doing the battery sizing calculations we take into consideration of continuous load, intermittent load and worst case tripping scenario which is in this case, Busbar protection operation. Considering the low to medium current discharge requirement and several hours of backup time, clearly X & H type batteries are not suitable for substation DC backup applications or let's just say these types are overkill. So the choice is left between L and M type. Although L type batteries should serve the most requirements for the substation DC backup application, we found that M type batteries serve the best of the both worlds. While M type batteries can provide several hours of backup time, it can also easily handle moderate spikes of discharge current in cases like Busbar protection operation etc. Naturally, the M type batteries would be slightly more expensive than the L type batteries for similar sizes; however, we believe the minor additional cost justifies the use of M type batteries for substation DC backup applications.

5. THE CHOICE OF CHARGER / RECTIFIER DESIGN – 6 PULSE vs 12 PULSE RECTIFIER

Substations battery chargers must be designed in such a way that it should be able to supply the continuous DC load and at the same time to be able to charge the battery. Essentially, the modern day DC charger design is based on rectifier technology. The charger will take 3-phase AC supply and use the rectifier to convert the AC into DC through a network of diodes. Presently 2 (two) main rectifier design options are used, namely 6-pulse and 12-pulse rectifiers. Since the number of diodes used in 12-pulse rectifier is greater than 6-pulse rectifier, naturally the 12-pulse rectifiers are more expensive. The question then arises – whether the extra cost of 12-pulse rectifier justifies or not.

To begin with, a 6-pulse rectifier will generate 5th and 7th harmonics whereas a 12-pulse rectifier generates 11th and 13th harmonics. Clearly, 11th and 13th harmonics are easier to filter out than 5th and 7th harmonics. Thus a 12-pulse rectifier requires a smaller harmonic filter. A further study shows [11] that **T**otal **H**armonic **D**istortion (THD) of input line current stays around 29-30% on an average in case of 6-pulse rectifiers whereas for 12-pulse rectifier, the THD of line current stay around 12-13% on an average. Therefore, 12-pulse rectifier draws a whopping 17% less THD than 6-pulse rectifier. This result justifies the use of 12-pulse rectifier over 6-pulse rectifier. Accordingly, we have adopted this design in our transmission substation DC system in DEWA.

6. THE CHOICE of DC SYSTEM ARRANGEMENT

Depending on the requirement and budget, a utility may choose variety of DC system topologies. The arrangements can vary from simplest use of single charger, battery and **DC D**istribution **B**oard (DCDB) to multiple chargers, batteries and DCDBs in order to achieve redundancy. Each topology has its own advantages and disadvantages.

6.1 Single Charger Single Battery Single DC Distribution Board

This is the simplest DC system arrangement a utility can adopt.

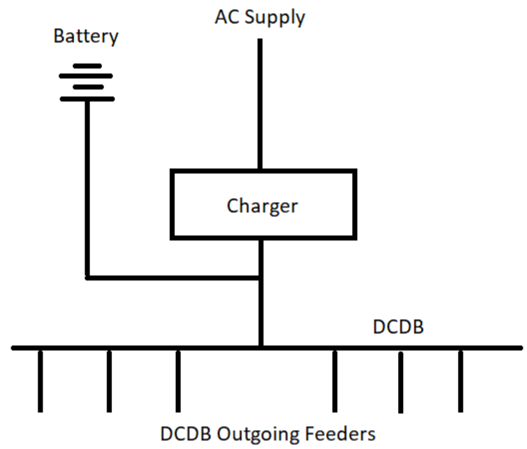

Fig 1: Single Charger, Battery & DCDB Arrangement

This arrangement is cheap, however, it does not give any redundancy. Any failure in charger will leave the station on battery backup. Any failure of battery will leave the station with charger without any DC backup. Any fault in DCDB will result in loss of entire DC load.

6.2 Dual Charger, Single Battery and DCDB Arrangement

This arrangement installs additional DC charger as a backup as shown in fig 2.

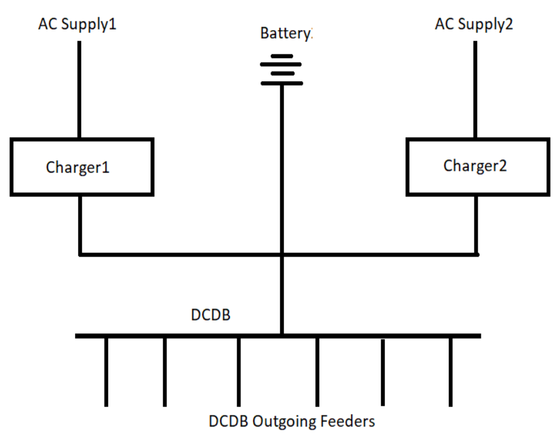

Fig 2: Dual Charger, Single Battery & DCDB Arrangement

Under normal operating condition, only one charger will be in service and the other charger will remain standby. In case of failure or maintenance of one charger, other charger will kick in and maintain the normal service. This arrangement provides decent redundancy in terms of maintenance and reliability.

6.3 Dual Charger, Battery and DCDB Arrangement

This arrangement offers much better flexibility in terms of redundancy and maintenance option as shown in fig 3.

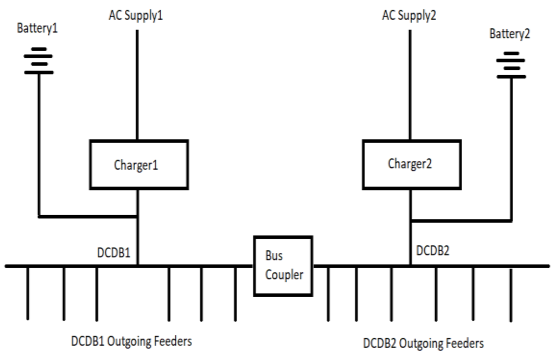

Fig 3: Dual Charger, Battery & DCDB Arrangement

Under normal operating condition, the Bus Coupler will remain open. Charger 1 will supply Battery1 and DCDB1 whereas Charger2 will supply Battery2 and DCDB2. This arrangement is ideal for utilities that prefer to have independent DC supplies for main-1 and main-2 protection relays. In case of failure of one of the DC systems (charger or battery or DCDB), other system is not getting effected and will continue to function as normal thereby fulfilling N-1 redundancy criterion. This arrangement is utilized by DEWA in typical 132/11kV or 132/33kV substations.

6.4 Dual Charger, Battery and Multi-Tier DCDB Arrangement

Some EHV/HV substations may use a more complex DCDB arrangement to achieve higher reliability. One such example is shown in fig 4.

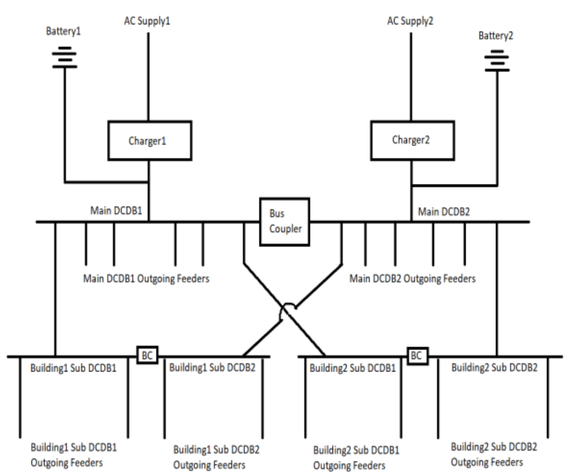

Fig 4: Dual Charger, Battery & Multi-Tier DCDB Arrangement

This kind of arrangement is very useful where multiple substation buildings are used for different voltage level in the same compound. The battery and the charger shall be designed in such a way that any failure of one system, other system would be fully capable of taking care of entire DC load of the substation. Most definitely, this arrangement is expensive; however, it provides excellent flexibility and reliability in terms of maintenance and forced outages which is required for critical substations. A typical 400/132kV substation in DEWA follows such arrangement.

7. FUTURE OF DC SYSTEM – WHAT A UTILITY MAY EXPECT IN NEAR FUTURE

The gradual advancement of DC system or overall power system may not be as eye catching as IT sectors, however, there has been remarkable achievements in charger technology. Modern day chargers are not just simple DC chargers; they provide ample features that make them highly efficient, reliable and near maintenance free.

Battery technology, on the other hand, is more traditional. Till today, Lead-Acid batteries and Nickel-Cadmium batteries dominate the power system applications. Having said that, there are some newer technologies that seem promising. One such option is Lithium Ion batteries. At present, Lithium Ion batteries are much more expensive than Lead-Acid and Ni-Cd batteries. However, as the technology gets more mature and with the increase of use cases; the cost of Lithium Ion battery is expected to come down over time. If we keep aside the cost part for now, we find that the Lithium Ion batteries provide very high energy density [6] when compared to Lead-Acid and Ni-Cd batteries. Not only that, Lithium Ion batteries provide excellent performance even at temperature as high as 60°C [6]. Thus, it could be an excellent choice in future for utilities located in MINA (**M**iddle **E**ast and **N**orth **A**frica) or other tropical regions with hot climate.

Despite showing great promises, Lithium Ion batteries may not enter into power system applications on a large scale basis in near future. Apart from the high cost, the utilities tend to be on the defensive side when it comes to new technology. They prefer to see it being used elsewhere and analyze the performance before adopting it in their own place.

8. CONCLUSION

The process of choosing Battery, Charger and DC System arrangement described in this paper was exclusive for Dubai Electricity & Water Authority (DEWA). Different utilities located in different geographical locations and with different requirements and budget may choose different options.

As the technology advances, different options may appear more viable than what is available today. As a progressive and leading utility in the MINA region, DEWA always strives to welcome new technologies that give better solutions, better performance without compromising the reliability of the existing system.

REFERENCES

[1] C. Sulzberger, IEEE Power and Energy Magazine, vol. 1, no. 3, pp. 64-67, 2003.

[2] L. de Andrade and T. de Leao, "A Brief History of Direct Current in Electrical Power Systems," in Third IEEE HISTory of ELectro-technology CONference (HISTELCON), Pavia, Italy, 2012.

[3] SAFT America, "Industrial Batteries 101," in IEEE PES FORT WORTH MONTHLY MEETING 17-Jul-2018, Fort Worth , Texas, 2018.

[4] J. Leuchter and P. Bauer, "Capacity of power-batteries versus temperature," in 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, Switzerland, 2015.

[5] J. McDowall, "Getting results with stationary batteries a basic guide to battery selection and maintenance," in IEEE Power Engineering Society Winter Meeting. Conference Proceedings, Columbus, OH, USA, 2001.

[6] J. McDowall, "Substation battery options-present and future," in IEEE Transmission and Distribution Conference, New Orleans, LA, USA, 1999.

[7] IEEE1188, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications," IEEE Std 1188-2005, pp. 1-44, 2006.

[8] IEEE450, "IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead-Acid Batteries for Stationary Applications," IEEE Std 450-2020, pp. 1-71, 2021.

[9] IEEE1106, IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented Nickel-Cadmium Batteries for Stationary Applications, 2015.

[10] "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Vented nickel-cadmium prismatic rechargeable single cells," IEC 60623:2017, pp. 1-48, 2017.

[11] A. a. T. a. A. M. Hernadi, "Modeling and Simulation of 6-Pulse and 12-Pulse Rectifiers under Balanced and Unbalanced Conditions with Impacts to Input Current Harmonics," in Second Asia International Conference on Modelling & Simulation, Kuala Lumpur, Malaysia, 2008.